Technical Report Documentation Page

1. Report No.
DCT/FAA/CT-95/4

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
User Benefits of Two-Way Data Link ATC Communications: Aircraft Delay and Flight Efficiency in Congested En Route Airspace

5. Report Date
February 1995

6. Performing Organization Code
ACW-500

7. Author(s)
Data Link Benefits Study Team

8. Performing Organization Report No.
DOT/FAA/CT-95/4

9. Performing Organization Name and Address
Department of Transportation
Federal Aviation Administration
Communications/Navigation/Surveillance Service
Atlantic City International Airport, NJ 08405

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
T2001E

12. Sponsoring Agency Name and Address
Department of Transportation
Federal Aviation Administration
IPT for Communication Aeronautical D/L Team
Washington, DC 20591

13. Type of Report and Period Covered
Final

14. Sponsoring Agency Code
AND-310

15. Supplementary Notes

16. Abstract

This report documents a Federal Aviation Administration (FAA) study that was conducted to demonstrate and quantify user benefits associated with the implementation of two-way Data Link air traffic control (ATC) services. The study was supported by the FAA Data Link Program Office (AND-310). The manned simulation research was performed at the FAA Technical Center by the Data Link Branch (ACW-500) of the Communications/Navigation/Surveillance Service.

19950404 107

17. Key Words
Data Link
NAS User Benefits
ATC Communication
Benefits Study

18. Distribution Statement
This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	126	

Form DOT F 1700.7 (8-72)

DOT/FAA/CT-95/4

FAA Technical Center
Atlantic City International Airport,
N.J. 08405

User Benefits of Two-way Data Link ATC Communications: Aircraft Delay and Flight Efficiency in Congested En Route Airspace

Data Link Benefits Study Team

February 1995

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

ACKNOWLEDGMENTS

The execution of this study was the result of many months of planning and the cooperative efforts of several individuals:

FAA Data Link Program

Ms. Karen Burcham was the Data Link Program Manager with overall responsibility for the program.

Ms. Barbara Cassada was the Data Link Division Manager responsible for the overall management and development of Data Link services.

Mr. Evan Darby, Jr. was the Test Director for the FAA Technical Center, and provided air traffic control, Data Link systems expertise, and test plan development.

Mr. Timothy Hancock was Test Director for the Atlanta ARTCC, and provided scenario, airspace and procedures development, controller training, air traffic control, traffic management, and Data Link expertise.

Mr. George Chandler provided test bed engineering and software in the development of Data Link services.

Mr. Cuong Le provided test bed engineering and software in the development of Data Link services.

Mr. Al Rehmann, ACW-520, was the Airborne Data Link Technical Program Manager.

Mr. Pocholo Bravo provided engineering support for the flight simulators.

Mr. John Kenton provided flight simulator communications support.

Other Organizations

Dr. Clark Shingledecker, NTI, Inc., provided research design and analysis as well as human factors support. He prepared the most significant portion of this report.

Mr. Craig Morris, Advanced Management Technologies Inc., provided technical program support for Data Link and test plan development.

Mr. James Simpkins and Mr. Ronald Tornese, The MITRE Corporation, developed Air Traffic Control Simulation Generator software, and assisted in scenario development and data reduction.

Mr. James Merel, UAL, Inc., implemented system modifications to the Host/Plan View Display (PVD) software.

Mr. Frank Buck, The MITRE Corporation, provided technical program support for Data Link and test plan development.

Ms. Virginia Stouffer, Martin Marietta, provided system performance measurements and economic benefit analysis.

Mr. Joe Lunder, TMA, Inc., provided air traffic control and automation systems expertise and test plan development.

Mr. Tung Le, LeTech, Inc., provided simulation modeling and system delay measurements.

Dr. Richard Mogford, CTA, Inc., coordinated flight simulator aircrew assessments.

<u>Atlanta Air Route Traffic Control Center Personnel</u>

Air Traffic Control Specialists:

Mr. Carl Dill Jr.	Mr. Mark Schoenhoff	Mr. Bret Simpkins
Mr. John Barganier	Mr. David Pedersen	Ms. Cicely Walker
Mr. Jeffrey Hunt	Ms. Deborah Crawford	Mr. William Ramsey
Mr. Kip Henry	Mr. Gregory Jones	Ms. Margaret Rosander
Mr. Donald Harkins	Mr. John Mahle	Ms. Deborah King
Mr. Barry Condon	Mr. Craig McKeand	Mr. John Davidson

Supervisory Air Traffic Control Specialists:

Mr. Robert Self	Mr. Charles Eisenlau	Mr. Richard Martinez
Mr. William Wertz	Mr. William Fitchpatrick	Mr. Michael King

Airspace and Procedures Specialists:

Mr. Jeffrey Bruner Mr. David Yarborough

Air Traffic Data Link Validation Team Support:

Mr. James Cherrey Miami ARTCC	Mr. Edward Brestle Fort Worth ARTCC

The Data Link Benefits Study Team:

Mr. Gregg Anderson	Mr. Joseph Lunder
Mr. Frank Buck	Mr. Craig Morris
Mr. Evan Darby, Jr.	Dr. Clark Shingledecker
Mr. Timothy Hancock	Ms. Virginia Stouffer

The Data Link Benefits Study Team wishes to thank the following groups and individuals for their cooperation and support:

Atlanta Air Route Traffic Control Center
National Air Traffic Controllers Association
The MITRE Corporation, Center for Advanced Aviation System Design
Mr. Jim Cha, AOR-100

Appreciation is also extended to the staff of the Technical Facilities Division, ACN-300, who provided the expertise required to keep the many NAS test systems operating in order to prepare and conduct this study.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED

Page

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF TABLES

EXECUTIVE SUMMARY

This report documents the results of the first Federal Aviation Administration (FAA) manned simulation study designed to demonstrate and quantify some of the benefits that would accrue to National Airspace System (NAS) users in return for equipping aircraft to receive domestic, two-way Data Link Air Traffic Control (ATC) services. Air traffic controllers, ATC supervisors, and professional pilots participated in high fidelity simulation tests in which a combined Data Link and voice radio communication system was used to control traffic in en route airspace.

The study demonstrated that controllers using two-way Data Link were able to provide ATC services that improved en route sector productivity and efficiency. These effects were reflected in reduced aircraft ground delay, flight time, and flight distance in comparison to a current operational environment using only voice radio communications. In all cases, the results were achieved with a margin of safety which met, or exceeded, current ATC standards, and with no indication of excessive controller workload. Economic cost savings associated with the findings were computed to determine the potential magnitude of two-way Data Link's impact and its significance to NAS users.

APPROACH.

The study addressed two operational en route ATC problems which have been attributed to limitations of the communications capability of controllers using the existing voice radio system. In both cases it was predicted that, by expanding the capacity of the communication channel, Data Link would permit controllers to improve the efficiency of traffic flow and reduce aircraft delays.

The first experiment tested the ability of two-way Data Link ATC communications to reduce airport departure delays that are caused by capacity problems in a high altitude en route departure sector. It was hypothesized that the increased communications capability provided by Data Link would alleviate ground delays by permitting the relaxation of miles-in-trail (MIT) restrictions which are routinely implemented for aircraft entering the sector.

The second experiment tested the ability of the Data Link to improve air traffic throughput in an en route sector where saturation is responsible for inefficient processing of aircraft arriving at a major airport. Because of

voice frequency congestion, controllers operating this sector often are unable to consistently supply aircraft at a rate which meets minimum restrictions for airport arrivals. In this case, it was hypothesized that effective use of the combined voice and Data Link capability would improve the timeliness with which aircraft are passed through the sector and delivered to the arrival fix, thereby reducing flight costs and delays.

The two experiments employed a case study methodology common to proof-of-concept research. Baseline Data Link test scenarios were built to precisely duplicate air traffic sample days taken from two airspace sectors within the Atlanta Air Route Traffic Control Center (ARTCC) which currently experience these problems. In both the departure and arrival cases, data on the delays experienced by traffic on the sample day were derived from the historical System Analysis Recording (SAR) tapes. Additional test runs were conducted using increased traffic levels representative of future demand.

Staffing for the two sectors was identical to that used for the peak traffic periods recorded on the sample day SAR tapes from the Atlanta ARTCC. Teams of three Atlanta controllers participated in the radar, data, and tracker control positions. Each team was accompanied by an ATC supervisor. In order to insure that the results were repeatable, three replications of the experiment were completed with different controller teams over the 6-week study period.

KEY RESULTS -- EXPERIMENT 1.

Experiment 1 addressed a sector in which the primary task is to control departures of jet aircraft climbing from the Atlanta airport. During the daily peak traffic period addressed in this study, traffic saturation currently requires the issuance of a 20 MIT restriction for departures entering the sector. This situation creates significant ground delays for all aircraft preparing to take off from the runway feeding the sector.

During testing with the combined Data Link and voice radio system, the subject controllers attempted to control comparable traffic at the current 20 MIT restriction, and with the traffic arriving at the sector boundaries at times corresponding to 15 MIT, 10 MIT, and with no restriction in force. In a fifth test run, Atlanta departures were increased by 10 percent with no restriction in force.

The results showed that the control teams in all three replications of the experiment were able to safely and effectively control the air traffic at each reduced spacing restriction, and with a 10-percent increase in departure traffic. No aircraft separation violations were detected by the Host computer under any of the test conditions. Furthermore, none of the operational assessments performed by the supervisors, controllers, or simulator pilots revealed any indication that the observed improvements in traffic handling capability were achieved with any compromise in the safety of ATC operations. A majority of the operational assessment ratings performed by the supervisors suggested that the margin of safety was greater than normal for sector during the peak traffic period when Data Link was used.

The direct user benefit associated with the performance achieved by the control teams using Data Link when no restrictions were placed on departing aircraft was a dramatic reduction in ground delays. Total delays for all departing aircraft decreased from 1,795 minutes with the 20 MIT restriction currently imposed at Atlanta to 687 minutes when the use of Data Link permitted the elimination of restrictions. Comparable savings were obtained with a 10-percent increase in traffic.

Measures of in-flight traffic flow indicated that the ground delay savings were not sacrificed by inefficient control of the aircraft once they had entered the sector. Moreover, the data show that using Data Link, the test controllers were able to provide service which reduced flight time and distance by 20 percent for all aircraft in the sector compared to their counterparts using only voice communications on the representative historical baseline day.

KEY RESULTS - EXPERIMENT 2.

In experiment 2, Data Link testing was conducted in an arrival sector where the primary task is to sequence aircraft inbound to the Atlanta airport. During two daily peak periods, traffic saturation typically creates a situation in which controllers cannot consistently provide minimum MIT to aircraft exiting the sector into approach control airspace. The volume of required communications often prevents efficient merging of traffic and forces the use of holding patterns and extensive vectoring. This delays arrivals and results in excess fuel consumption.

During initial testing with a combined Data Link and voice radio communications system, Atlanta controllers attempted to control traffic in

a scenario which reproduced the air traffic demand recorded for sector 09 on the historical SAR tape for one of the daily peak periods. Subsequent test trials increased the volume of arrivals by from 10 to 40 percent.

The results indicate that all three teams of test controllers were able to control the arriving Atlanta aircraft in sector 09 more efficiently with Data Link than their counterparts using only voice radio on the historical baseline day. While the average arrival on the baseline day flew approximately 111 miles over 18 minutes in the sector, the average controller team using Data Link was able to reduce the distance flown to 89 miles over 14 minutes with the identical traffic sample. When the traffic sample was increased by up to 40 percent, the data show that the arrival aircraft maintained an advantage of 3 to 4 fewer minutes of flight time in the sector when Data Link was used to expand the ATC communications channel. In all cases, these improvements were achieved through more strategic sequencing of the arrival traffic streams, the elimination of holding patterns, and more direct clearances to the arrival fix.

Control teams in all three replications of the experiment controlled the air traffic safely and effectively. No aircraft separation violations were recorded. Furthermore, their were no indications that the observed improvements in sector throughput were achieved with any reduction in operational safety. All supervisor, controller, and pilot operational assessments indicated that the margin of safety during the Data Link test was equal to, or greater than, that experienced at the actual sector during the peak arrival traffic period using only voice communications.

ADDITIONAL FINDINGS.

A variety of subsidiary measures were collected during both experiments to support the primary benefit measures. ATC supervisor evaluations of key sector tasks indicated that controller performance was within normal limits, or better, for all Data Link test runs. Furthermore, controller ratings and measures of handoff latency yielded no evidence of excessive controller workload with Data Link.

The performance benefits demonstrated in the experiments were associated with reductions of 78 to 84 percent in voice radio channel occupation time as Data Link was used to send most clearances and transfer of communication messages to equipped aircraft.
In addition, the data show that the test control teams distributed communications responsibilities among all three members, permitting

optimal use of the expanded communications channel and increased sector productivity.

NAS USER COST SAVINGS.

The direct effect of Data Link addressed in this study is its ability to increase the capacity of the communications channel between controllers and pilots. When applied to en route airspace sectors currently affected by frequency congestion, the results of the study showed that by permitting more timely and effective clearance delivery, a communications system combining voice radio and Data Link can reduce aircraft delays and increase operating efficiency.

The final task of this study was to translate the system performance improvements observed in the experiments to estimates of the annual cost savings that would be received by NAS users. Initial estimates were computed directly from the performance data for the test sectors at the Atlanta ARTCC. In both cases, these projections were restricted to the two sectors over the two, 1-hour peak traffic periods. The predictions were based on current FAA statistical computations of the average, per-minute cost to air carriers for taxi and in-flight delays. Total savings attributable to the reduced ground delays and flight times demonstrated with Data Link for the two sectors were in excess of 8.6 million dollars annually.

An estimate of national annual benefit was computed from the results of a national sector survey and the findings of the two experiments conducted for this study. The results show that over 9,600 flights are affected nearly every day by communications-related saturation in the 43 sectors identified by the survey. These flights experience 7,980 aircraft-days of delay per year. The total estimated annual cost savings to NAS users associated with implementing two-way Data Link ATC communications would be over 337 million dollars.

In evaluating the significance of these findings, it should be remembered that the calculated cost savings are restricted to Data Link's ability to increase ATC communications capacity in a single domain of ATC operations. Safety and efficiency enhancements that may result from two-way Data Link's capability to improve the accuracy of communications, and from its use in other ATC environments are expected to significantly increase estimated cost savings to aircraft owners and operators.

1. INTRODUCTION.

1.1 PURPOSE.

This report documents the results of the first in a planned series of studies designed to assess benefits associated with the implementation of domestic, two-way Data Link air traffic control (ATC) services. Real-time, manned simulation testing was used to measure some of the quantifiable benefits that would accrue to aircraft owners and operators for investing in avionics equipment to receive these services. Incidence data collected from ATC facilities throughout the National Airspace System (NAS) were then employed to produce nationalized estimates of net annual benefits associated with the test results.

The work reported here specifically focused on the effects of introducing Data Link communications to en route ATC environments where aircraft delay and operating efficiency are influenced by saturation of the air-ground communications channel. Future studies and analyses will examine additional benefits and other ATC environments.

1.2 BACKGROUND.

1.2.1 Data Link Implementation Plans.

Over the past several years, the Federal Aviation Administration (FAA) has evolved a comprehensive plan for building an air traffic management (ATM) system. This system will support future global flight planning, aircraft operation, and ATC services through the introduction of advanced communications, navigation, and surveillance technologies. A key feature of the future ATM system will be the use of digital data communications as a primary means for exchanging aeronautical information and delivering ATC services.

The FAA plan currently calls for implementation of domestic, in-flight Data Link ATC services to begin in 1998 with the introduction of two-way communications in the en route and terminal ATC environments. At this initial stage, controllers will have the capability to uplink a variety of clearance and advisory messages to equipped aircraft, and aircrews will be able to downlink reports and ATC requests. Performance standards and a message dictionary for these two-way Data Link communications have been published by RTCA (1993).

Within the next several years, Data Link implementation will begin to expand to a broad range of automated information exchanges. These end-state applications will provide a connection between airborne and ground-based data and computing resources that will optimize approach traffic flow, enable the routine use of 4-D navigation and permit long range conflict detection and resolution.

Execution of the plan outlined above will require extensive cooperation between government and private industry, and major resource investments by both parties. The FAA must create the integrated telecommunications network needed to support Data Link and develop associated ATC software and controller interfaces. In order to justify the ground-based investment, users of the NAS must make a simultaneous decision to equip a significant number of aircraft with the avionics and aircrew interfaces needed for Data Link communications.

1.2.2 Justification for Early Data Link Equipage.

The success of the phased introduction of Data Link ATC services promoted by the FAA plan will depend on growth in airborne equipage levels during the initial stage. This early build-up will permit thorough validation of the communications system, making the later introduction of Data Link-mediated automation more technically feasible and cost-effective.

There is general agreement among both government and NAS user representatives that significant improvements in the efficiency of airborne operations will be achieved when Data Link is used to enable advanced automation. However, because of the current lack of evidence for immediate economic benefits associated with domestic two-way Data Link ATC services, the case for equipping aircraft during the first stage of implementation has not met with widespread acceptance. In response to these concerns, the FAA has elected to initiate a program of a real-time, manned simulation research to identify and quantify benefits that will accompany the implementation of a two-way Data Link system for controller-pilot ATC communications. The study described in this report was conducted by the FAA to address these overall goals.

1.3 DIRECT EFFECTS OF DATA LINK.

Any economic benefits that may be associated with the initial two-way Data Link capability will be realized indirectly through changes in ATC

capabilities and performance that are made possible by this technology. For this reason, the process of defining a study to assess these benefits began by examining some problems which exist in ATC communications, and the effects that the introduction of Data Link can be expected to have on them.

1.3.1 Frequency Congestion.

One of the primary factors that has driven the development of Data Link has been the growing utilization of voice radio in the NAS. Because the voice channel is available to only one speaker at a time, increasing traffic volume rapidly leads to frequency congestion. When the channel becomes saturated, system performance suffers as ATC clearances become less timely and the exchange of information is reduced to an absolute minimum.

In order to understand how Data Link is likely to affect ATC system capabilities, it is important to examine the way in which controller performance is affected by frequency congestion. When debriefing controllers about the factors which influence workload experienced on the job, the demands associated with monitoring the radar display or making decisions about appropriate control actions are rarely mentioned. Instead, it is common to hear that "it's not the number of aircraft in my sector that creates workload, but what I have to do with them and how much time I have to do it."

Such statements emphasize a close relationship between workload and the amount of communication required to maintain control over air traffic. They also suggest that any factor which limits the amount of time available to perform required communications with aircraft will increase controller workload or reduce the efficiency with which ATC tasks can be accomplished. As frequency usage is increased, high workload is precipitated by a proportional limitation in the time available to carry out required communications, rather than an inherent inability of the controller to handle the air traffic or by saturation of the airspace itself.

From a theoretical point of view, this workload problem can be seen as a special combination of the data limitations and resource limitations on human performance discussed by Norman and Bobrow (1975). In the case of frequency congestion, constraints imposed by the simplex nature of the radio system produce a data limitation on controller performance by preventing timely communications. That is, performance is limited by the

physical constraints of the system rather than the information processing resources of the controller. However, as a result of the shrinking performance windows, mental resource limitations come into play and workload increases as the controller attempts to maintain system performance by employing tactical control strategies which tax his perceptual, cognitive, and speech-motor capacities.

Because of the close coupling between the controller's ability to make effective use of available system capacity and voice frequency usage, a fundamental measurement taken during high fidelity Data Link simulations at the FAA Technical Center has been the extent to which Data Link reduces use of the radio channel to communicate with aircraft. In each of these studies, subject controllers are asked to control simulated air traffic using traditional voice communications alone, and under conditions where both voice and Data Link channels are available. During Data Link trials, the controllers are instructed to perform the ATC task as safely and efficiently as possible, and to use the communications system that they feel is most effective for accomplishing their objectives.

Data Link's effect on voice radio frequency usage has been measured in both en route and terminal simulation studies. In an en route operational evaluation, the provision of an initial service capability (transfer of communication and altitude assignment) reduced the number of voice transmissions initiated by controllers up to 41 percent. It also reduced the total amount of time that the controllers occupied the radio frequencies up to 45 percent (Talotta, et. al., 1990). Furthermore, as the proportion of aircraft in the test scenarios equipped with Data Link was raised from 20 to 80 percent of the total number presented in the test scenario, the overall efficiency of ATC communications improved as requirements for repetitions of voice messages and clarification of misunderstood clearances decreased.

Similar dramatic reductions in voice radio usage were obtained in terminal testing under 75 percent aircraft Data Link equipage. In this situation, where controllers could transmit speeds, headings, and initial contact responses as well as the services used in the en route study, the number of voice messages issued by controllers dropped by 50 percent over the voice-only test conditions, and radio channel occupation time by controllers fell by 60 percent(Data Link Development Team, 1991).

Taken together, the results of the studies cited above, and others obtained in high fidelity simulation research at the FAA Technical Center, make two

important points about Data Link ATC communications. First, they demonstrate that, given an appropriate human-computer interface, ATC communications using Data Link can be conducted effectively in the context of the air traffic controller's complex and dynamic task environment. Second, the findings show that controllers can utilize the traditional voice channel along with Data Link to effectively expand the capacity of the air-ground communications channel.

1.3.2 Communications Errors.

In addition to its potential for reducing communications-induced limitations on effective system capacity, analyses performed by the FAA Technical Center also have indicated that Data Link has the ability to reduce the occurrence of common ATC communications errors that affect flight safety and efficiency. Incidence estimates available from a number of sources clearly show that communications problems are a major source of concern in the present ATC system. In 1988, the FAA noted that 23 percent of all operational errors (minimum aircraft separation violations) were caused either directly or indirectly by communications mistakes. Similarly, compilations of reports provided on a voluntary basis by aircrew and controllers to the Aviation Safety Reporting System (ASRS) have indicated that 70 to 80 percent of all potentially hazardous incidents that are reported implicate ineffective verbal information transfer; and that a clear majority of these involve air-ground radio communications (Billings and Reynard, 1981; FAA, 1988).

Common categories of human error which appear to be the primary sources of the cited communications problems include acoustic confusion and transposition of alphanumerics, pilot readback error, controller "hearback" error, misinterpretation caused by poor pronunciation and failure to use standard phraseology, and improper radio keying technique.

Shingledecker and Talotta, (1993) discussed how several general human performance limitations appear to combine with the features of a simplex voice radio system to promote the errors that are commonly observed in the ATC environment. These traits include: (1) the limited rate at which humans can produce and comprehend the speech signal (partially defining the point at which radio frequency congestion becomes problematic), (2) short term memory limits for the content of the transient acoustic displays used in radio communications, (3) the tendency to rely on expectation in the absence of unambiguous data, (4) human susceptibility to phonetic confusion in acoustic displays, (5) the relative unreliability of the human as

a monitoring device in a multiple task environment, and (6) the tendency for humans in a high workload situation to adapt by shedding load, often sacrificing highly redundant, prescribed communications formats.

Unlike voice radio, Data Link offers a communications medium which transmits coded, digital data to individual addressees. This feature of Data Link can be expected to alleviate the problems induced by the human-system interaction at nearly all stages of the communications process. While Data Link cannot compensate for poor controller decisions, the message formulation stage should be improved by providing reasonableness and logic checks of the digital data. Message composition can be assisted by storing common messages for selection from a menu, and by employing automatic checks on controller input formats to prevent the transmission of ambiguous clearances. Furthermore, message composition would not be impeded by the delays experienced when the radio channel is in use by pilots.

Message transmission also will be improved because Data Link will assume some portion of the load on congested radio frequencies. As discussed in the previous section of this paper, this will not only increase the availability of the voice frequency, but also reduce controller workload and increase the timeliness of clearance delivery by permitting controllers to communicate when necessary -- not merely when the channel is available. In addition, those messages carried by Data Link will be effectively immune to degradation by noise and blocking that plague an analogue radio system and impair pilot perception. Monitoring failures and message (call sign) detection by the pilot will be totally eliminated as a source of error since this task will be assumed by Data Link's discrete addressing system. Likewise, message interpretation will be enhanced because pilots will have a persistent, storable reference of message content, and because available evidence suggests that a visual display may be less prone to misinterpretation than an acoustic display.

Finally, the acknowledgment and verification stage of the communications process, which is a human responsibility in the voice radio system, will be largely allocated to Data Link. However, rather than being assumed by Data Link in an analogous sense, the verification process will be built in each transmission as the system automatically verifies the integrity of message content reaching the pilot, assures the controller that the responding aircraft is the intended receiver, and monitors for failed confirmatory downlinks.

Based on the analysis summarized above, Shingledecker and Talotta (1993) attempted to estimate the extent to which the introduction of Data Link will ameliorate communications errors. Using ASRS data collected between 1980-1984 including 2,700 reports of communications problems, their findings indicate that Data Link would produce a major reduction in communications problems that form 45 percent of all reported communications incidents. These include ambiguous, incomplete, and garbled messages, failures to detect clearances, phonetic confusions, and transposition errors. A further 54 percent of incidents would be at least partially reduced by Data Link. These include untimely issuance of clearances caused by congested or blocked frequencies and those cases where aircraft perform uncleared maneuvers because of confusions about the intended receiver of a message or because of misinterpretation of the clearance itself. Only 1 percent of all problems would be unaffected, these being situations where the controller issues a logically reasonable, but erroneous clearance because of faulty decision making.

1.4 STUDY RATIONALE.

The data and analyses discussed above suggest that the introduction of two-way Data Link ATC services will significantly improve NAS operations by reducing communications errors and by increasing communications channel capacity. However, the task of using these indications of the direct effects of Data Link to produce estimates of their associated economic benefits is complicated by the fact that the benefits are clearly *context specific*. Unlike the addition of a new parallel runway at an airport or the development of a more fuel-efficient aircraft engine, two-way Data Link ATC communications are not expected to save money on every flight or to prevent all airborne mishaps. Instead, the observable benefits of Data Link will be displayed only under those conditions where restrictions in communications capability and communications errors significantly affect the quality and cost of aircraft operation.

Because of this, the study described in this report was based on the assumption that sensitive measurements of the economic impact of Data Link would not be obtained by randomly sampling ATC scenarios occurring in the NAS. Rather, these measures would be required to focus on those specific ATC situations and conditions under which Data Link's direct effects would be expected to ameliorate the underlying cause of inefficiency or delay. Thus, the approach developed for this study involved testing under a sample of ATC scenarios in which Data Link's known effects are expected to translate directly to quantifiable economic benefits.

To insure that these scenarios were representative of existing air traffic phenomena, they were selected from recent historical records of actual NAS operations.

2. STUDY OBJECTIVES.

The primary objective of this study was to measure and demonstrate some of the benefits that will be gained by commercial NAS users in return for equipping aircraft to participate in two-way Data Link ATC communications. Specifically, the study employed real-time, high fidelity manned ATC simulation to assess the extent to which the increased communications capacity provided by Data Link can (1) reduce aircraft spacing restrictions and departure delays, and (2) reduce aircraft operating inefficiencies when used in two en route airspace sectors where ATC operations are routinely limited by communications-related sector saturation.

A second objective of this study was to use the local benefits obtained from the empirical results of the experiments to project system-wide benefits under current and future air traffic demand scenarios.

Finally, the study was used as an opportunity to address a number of subsidiary objectives associated with the use of Data Link at en route sectors manned by multiple air traffic controllers. These included an initial exploration of communications procedures for control teams, and an identification of human-computer interface requirements to support optimal team performance.

3. SUMMARY OF APPROACH.

In the study described in the succeeding sections of this paper, two operational ATC problems were addressed. These problems have been attributed to limitations of the communications capability of controllers using the existing voice radio system. In both cases, the benefits of Data Link were hypothesized to be associated with decreases in aircraft delays and flight time made possible by the expanded communications channel. Anticipated benefits resulting from the enhancement of communications accuracy and related safety improvements were not explicitly considered in this study.

The first experiment tested the ability of two-way Data Link ATC communications to reduce airport delays that are caused by capacity

problems in a high altitude en route departure sector. It was hypothesized that the increased communications capability provided by Data Link would alleviate ground departure delays by permitting the relaxation of spacing restrictions which are routinely implemented on traffic entering the subject sector.

The second experiment tested the ability of Data Link to improve air traffic throughput in an en route sector where sector saturation is responsible for inefficient processing of aircraft arriving at a major airport. Because of voice frequency congestion, controllers operating these sectors often are unable to consistently supply aircraft at a rate which meets minimum restrictions for airport arrivals. In this case, it was hypothesized that effective use of the combined voice and Data Link capability would improve the timeliness with which aircraft are delivered to the arrival fix, thereby reducing flight costs and arrival delays.

The two experiments employed a case study methodology common to proof-of-concept research. Rather than synthesizing scenarios based on a general concept of the types of ATC problems discussed above, test scenarios were built to precisely duplicate air traffic data sample days taken from two airspace sectors within the Atlanta Air Route Traffic Control Center (ARTCC) which currently experience these problems. For the departure case (experiment 1), baseline data on the delays experienced by traffic on the sample days were derived from the historical System Analysis Recording (SAR) tapes. The tapes also were used to create Data Link test scenarios which present departure demands identical to those experienced on the sample day. During testing, miles-in-trail (MIT) restrictions were incrementally reduced to determine the capability of subject controllers to handle the increased flow using the combined voice and Data Link communications systems. The difference between aircraft ground delays experienced in the historical baseline when the standard MIT restriction was introduced and those achieved in simulation with Data Link were used to determine accrued benefits.

For the arrival problem (experiment 2), baseline data on aircraft flight paths and arrival delays for the affected sector were computed from information contained in the historical SAR tapes for the sample day. As in the departure problem, the SAR tapes also were used to create Data Link test scenarios that mimicked the original aircraft crossings into the sector. During testing, data were collected to assess sector throughput and flight distance when controllers used a combined voice and Data Link

communications system. Comparisons between the historical baseline and the simulation results were used to compute associated tangible benefits.

In both experiments, additional test runs were completed with increased traffic levels representative of future demand. These data were used in conjunction with estimates generated by a fast-time simulation model to assess the impact of Data Link in comparison to retaining a voice-only system as traffic volumes grow. Furthermore, in both experiments, objective measures as well as controller, supervisor and pilot evaluations were used to insure that any measured benefits were achieved within acceptable limits of safe ATC and aircraft operations.

An effort was made to generalize the results of the study by determining the incidence and nature of communications-induced inefficiencies in domestic en route airspace. Sector saturation problems similar to those tested in the Atlanta ARTCC were identified by conducting a structured survey with supervisory personnel in ARTCCs throughout the U.S. These data were used to extend the local study results to an estimate of the annualized national economic benefit that would be achieved with Data Link in congested en route airspace.

4. TEST CONDUCT.

4.1 TEST FACILITIES.

4.1.1 Facilities Description.

The two real-time experiments performed for this study were conducted in ATC simulation facilities located at the FAA Technical Center. The specific laboratory configuration for the study included three key components of the FAA Technical Center facilities: the NAS en route laboratory; the Target Generation Facility (TGF); and the Data Link laboratory (figure 1).

The NAS en route laboratory contains the Host computer system used for NAS enroute data and radar processing. The Host communicates with several suites of the Plan View Display (PVD) controller workstations that are used to display radar and system data and to enter system inputs. The laboratory appearance is identical to an operational en route control area and includes a full voice communications system and flight strip printers.

Current Atlanta ARTCC field-release software was implemented on the

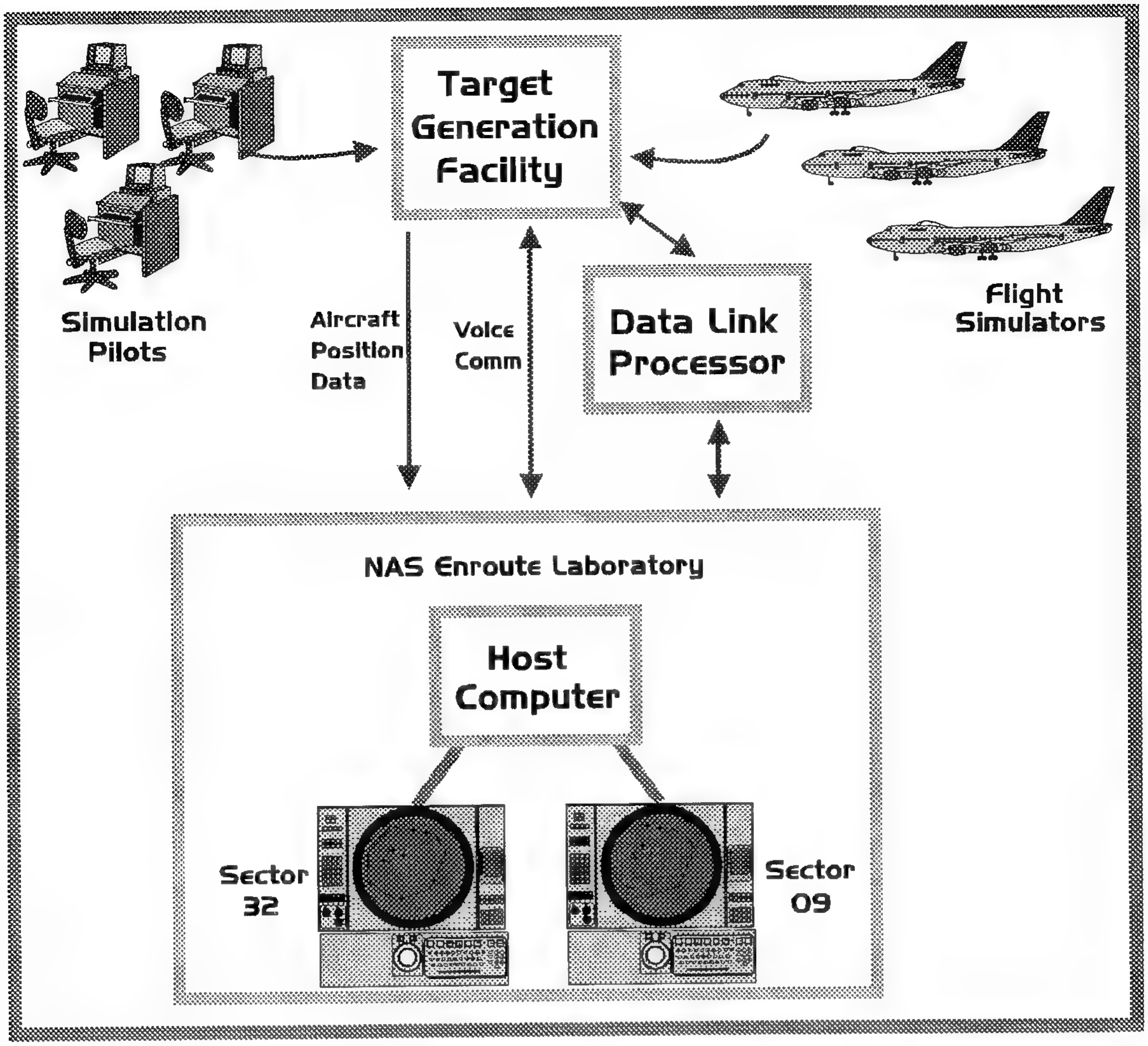

FIGURE 1. FAA TECHNICAL CENTER SIMULATION FACILITY CONFIGURATION FOR DATA LINK BENEFITS STUDY EXPERIMENTS

NAS laboratory Host computer for the present experiments. Minimal software modifications were completed to accommodate Data Link communications. SAR tapes identical to those normally generated by the Host computer during field operations were used to collect data on aircraft position and time variables. They also permitted analysis of Data Link inputs and of any aircraft separation violations.

The NAS laboratory is linked to the TGF through the Host computer. The TGF permits the Host and the PVD workstations to act as a functioning control facility by providing simulated radar data and a means for

interaction between aircraft and controllers. The TGF includes a laboratory in which pseudopilots operating from specialized computer terminals can carry out voice and Data Link communications with controllers and make inputs to realistically maneuver aircraft in response to ATC clearances. In addition, the TGF can be linked to remotely located, full fidelity aircraft flight simulators in order to permit certified pilots to participate in air traffic scenarios.

TGF pseudopilots represented a majority of the aircraft participating in the test scenarios for the present study. However, six flight simulators flown by professional pilots also were used during testing. These included two B727 simulators remotely located at Avia Research in California, and at the FAA Mike Monroney Aeronautical Center in Oklahoma (OKC), and two B747 simulators located at the NASA Ames Research Center in California, and at the National Research Laboratory (NLR) in the Netherlands. The final two simulators were a General Aviation Trainer (GAT) and the Reconfigurable Cockpit Simulator (RCS), both situated locally at the FAA Technical Center in New Jersey.

The Data Link laboratory houses a VAX 11/750 computer which acts as an emulation of the future ground Data Link processor. The VAX supported all Data Link communications among controllers in the NAS en route laboratory, TGF pseudopilots, and aircraft flight simulators.

4.1.2 Facility and Scenario Validation.

The primary function of the FAA Technical Center simulation facilities is to support the analysis and testing of ATC problems that arise during ongoing field operations. Because of this, the test hardware and software are identical to those currently used in NAS operations. For the purposes of the present study, this direct emulation capability helped to insure that the ATC scenarios and controller interfaces used in laboratory testing would recreate the conditions and controller work environment which existed on the baseline sample days in the Atlanta ARTCC.

The Atlanta ARTCC supplied the SAR and voice radio tapes for the two test sectors that were used to create the baseline test scenarios. The ARTCC was asked to provide a single sample day tape for each experiment that would provide a representative example of the daily rush period problems experienced by the two sectors. The ARTCC was specifically requested not to select sample days during which weather or atypical events complicated the ATC environment.

The sample day that was provided for both sectors was April 18, 1994. The call signs, flight plans and types of aircraft that were used in the test scenarios for the two experiments were identical to those recorded on the sample day SAR tapes. Winds aloft in the simulation test scenarios were matched to the sample day based on records provided by the National Oceanic and Atmospheric Administration (NOAA) for the Athens, Georgia, reading on that date.

Because the validity of the data collected in this study depended upon direct comparability of the operational sectors and the test environment, personnel from the Atlanta ARTCC were asked to evaluate the fidelity of the simulation. As described in section 4.4.2, prior to the study, two controllers who were qualified at the test sectors and who worked as area airspace and procedures specialists participated in exercises intended to develop preliminary communications procedures for the test scenarios. During these exercises, the controllers examined sector equipment layouts and controlled traffic in the test scenarios. At the conclusion of the effort, they were asked to provide written input regarding required changes to the hardware configuration, the sector adaptation, and any other factors which may have affected the quality of the simulation.

Both controllers indicated that the scenario traffic was typical for the rush periods at the two test sectors. In addition, they certified that the simulation contained no artifacts which would reduce controller workload in comparison to the actual operational sectors. The physical layouts of the sector workstations also were judged to be identical to the operational sectors. The single required change identified by the Atlanta procedures specialists was the repositioning of a keyboard at one of the test sectors. This modification was made prior to the start of the study.

Additional data confirming the validity of comparisons between the simulation data and that recorded at the operational facility were collected during debriefing sessions with the test controllers and their supervisors. These results are presented in section 5.4.1 of this report.

4.2 DATA LINK PERFORMANCE, SERVICES AND AIRCRAFT EQUIPAGE.

The Data Link message transmission times for these experiments were controlled by the Data Link laboratory equipment. This equipment emulated the temporal characteristics of Data Link communications

implemented on a Mode Select (Mode S) radar system. Because Mode S is a narrow beam radar, uplink and downlink times are determined by the rotation speed of the antenna and the relative position of the aircraft. For the present study, a 6-second scan period was assumed. The Data Link laboratory simulated this configuration by randomly selecting uplink delays from a rectangular distribution ranging from 0 to 6 seconds. For downlinks, Mode S delays are partially dependent upon the latency of the aircrew's response to the uplink. If the response time is less than the time needed for a single scan, the average downlink delay will be equal to the scan period of 6 seconds. However, if pilot response delays are longer, downlink delays will increase in even multiples of the scan period. Thus, for the present study, the Data Link laboratory equipment returned downlink responses entered within 6 seconds of uplink receipt with a 6-second delay, responses entered within 12 seconds with a 12-second delay, etc.

While estimated Mode S data transmission characteristics were assumed for this study, the findings of the experiments should be valid for any medium that would produce a range of system and human response delays simular to that experienced by the subject controllers. For purposes of comparison to other Data Link transmission media, and to permit identification of the actual range of response delays under which results were collected for this study, total transaction time data were collected for each Data Link transaction initiated during testing. Total transaction time measurements included uplink and downlink delays as well as pilot response latencies. These data are presented in section 5.3.3.

During testing, pilots and controllers had the capability to employ a range of two-way Data Link ATC communications. The message set conformed to the standards defined in DO-219 (RTCA, 1993). The set included transfer of communication messages, as well as altitude, speed, and heading clearances. Initial contact messages were downlinked from the equipped aircraft, and unconstrained, free text uplink messages were available for use.

While they are specified in the DO-219 message set, downlinks of pilot requests, (e.g., requests for altitude or route changes) were not available for use during the simulation. Because such aircrew requests are very uncommon in the arrival and departure scenarios that were tested in this study, and did not appear in transcripts of the voice recordings for the historical sample days at the Atlanta ARTCC, the absence of this

downlink capability was expected to have minimal impact on the study outcome.

Approximately 90 percent of the aircraft in each test scenario were equipped to conduct Data Link ATC communications in addition to voice radio communications. To the extent possible, the 90-percent equipage level was achieved by assigning Data Link to the newest commercial carrier and business aircraft from the sample day SAR tapes in order to realistically portray likely future equipage schedules.

4.3 TEST SUBJECTS.

The subjects for the two experiments were 18 Full Performance Level (FPL) en route ATC specialists recruited from the Atlanta ARTCC who regularly worked at the study test sectors. The nine subjects for experiment 1 were controllers from a high altitude en route departure sector (Sector 32, Area 2). The nine subjects for experiment 2 were controllers from an en route arrival sector (Sector 09, Area 5). In accordance with current labor agreements, all subjects were selected for participation in the study by local Atlanta representatives of the National Air Traffic Controllers Association.

Three controllers staffed each of the test sectors during the rush periods on the historical sample days that were used as the baselines for testing. For this reason, the subjects in both experiments participated in teams of three controllers. Control position assignments were made by mutual agreement of each team with one controller at the radar (R) position, one at the data (D) position, and the third at the tracker (T) position. The controllers maintained their position assignments throughout the test trials.

The two experiments were conducted simultaneously with one team from each sector participating in each of three replications. The replications were completed over three consecutive 2-week study periods. Each of the control teams was accompanied by a different supervisor from its Area of the Atlanta ARTCC.

4.4 TRAINING AND PROCEDURES DEVELOPMENT.

In order to maximize the validity of the performance data collected in this experiment, extensive efforts were made to accurately simulate the working environment and conditions of an operational ATC facility. As

discussed in previous sections, these efforts included the use of actual NAS equipment and the selection of subject controllers who were thoroughly familiar with the test airspace. They also included an attempt to provide the subject controllers with a knowledge of Data Link and a level of proficiency in using it that they would be expected to have in an operational facility where Data Link had been recently implemented. Thus, subjects received extensive training and practice in Data Link operation.

4.4.1 Training.

The subjects were trained in the use of the Data Link system in classroom sessions and participated in team practice sessions in the en route NAS laboratory. Training took place over the first 4 days of each study session. The first day was devoted to briefings which described the Data Link displays and inputs. These were followed by an initial laboratory practice session during which facilitators were available at each sector. The second and third days of training consisted of laboratory practice sessions in which traffic levels were raised progressively from 40 to 80 percent of that experienced on the historical baseline days. The final training day included practice at traffic levels equal to the baseline days, as well as instruction on the rating and questionnaire instruments that were used during testing.

A Data Link training manual was provided to the subjects for use in classroom sessions (FAA Technical Center, 1995). Laboratory training days began with a group discussion during which any questions on Data Link operation were addressed. Each controller team received an average of 17 hours of laboratory practice prior to the start of data collection.

All simulated aircraft were equipped with Data Link during early training sessions to focus on basic practice with the new communication medium. Later sessions reduced equipage to the 90-percent level used during testing to permit practice in alternating between voice and Data Link usage. The later practice sessions used scenarios which presented air traffic demands that were similar to the test scenarios in terms of the general pattern of arrival at the sector boundaries, mix of aircraft types and call signs. Thus, during the training phase of the experiment, the controllers experienced demands representative of daily variations at the test sectors. However, to avoid bias attributable to anticipation of a specific traffic pattern, the configurations of air traffic arriving at the sectors that were

dictated by the sample day SAR tapes were presented only during actual testing.

4.4.2 Data Link Procedures.

As they would in an actual implementation of the system, the controllers also participated in exercises to develop efficient procedures for applying Data Link to the type of air traffic encountered in their sectors. Prior to the study, consulting procedures specialists from the Atlanta ARTCC assisted test personnel in developing preliminary procedures for the scenarios that included use of Data Link by the controller teams. These procedures prescribed general strategies for dividing different message types between voice and Data Link as well as for the division of Data Link duties among the three control positions.

The baseline procedures were introduced to the test subjects in a briefing conducted after the second day of training. They were encouraged to evaluate, refine and modify these procedures within their control teams during subsequent practice sessions. Each team described its finalized procedures during a debriefing held prior to the last practice session. Data on the procedures adopted by the control teams are reported in section 5.3.1.

4.5 EXPERIMENT 1 -- DEPARTURE SECTOR.

4.5.1 Test Scenario.

The test scenarios for experiment 1 were based on a recent historical sample of air traffic derived from sector 32 (Spartanburg) in area 2 of the Atlanta ARTCC (figure 2.). The primary task of this high altitude (FL 240 to FL 290) en route sector is to control departures of jet aircraft climbing from the Atlanta and Charlotte airports. In addition, sector 32 handles arrivals into Charlotte and overflight traffic. On a daily basis during the early afternoon, traffic saturation in this sector reaches a level which necessitates the issuance of a 20 MIT restriction for Atlanta departures entering the sector. This situation creates significant ground departure delays for all aircraft using the runway that serves the affected sector.

The experiment was designed to determine whether the MIT restrictions could be relaxed with the introduction of Data Link communications. In

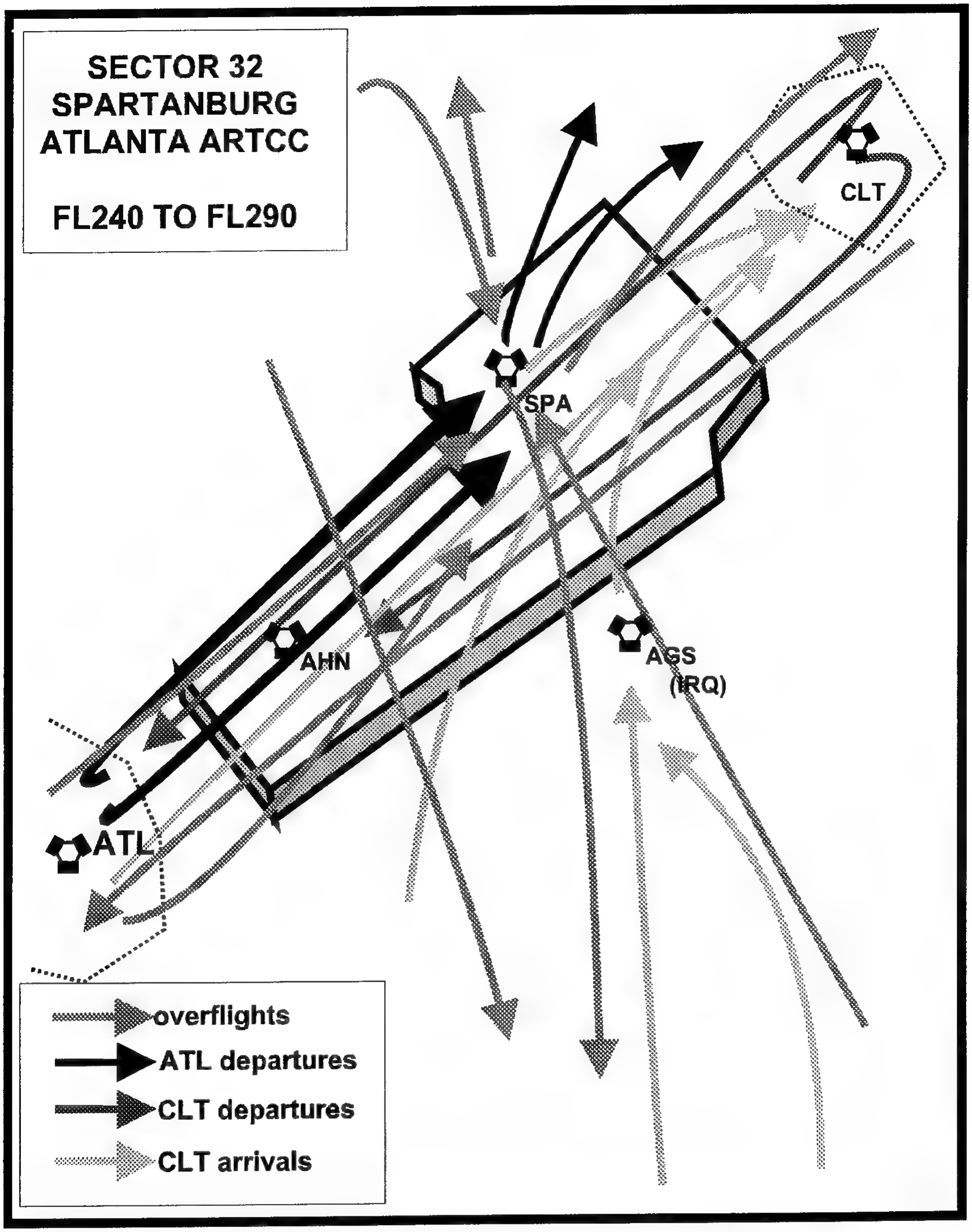

FIGURE 2. DEPARTURE SECTOR EXPERIMENT 1

the test scenarios, traffic demand at the boundaries of sector 32 was accelerated from the original sample SAR tape record to produce three levels of reduced MIT restriction.

4.5.2 Testing Methodology.

Following the training and practice sessions, each control team participated in five test sessions in which both Data Link and voice radio were available for ATC communications. Each test session consisted of a 1-hour period of ATC simulation during which the team controlled traffic in a scenario derived by varying the MIT restriction on departure aircraft from the Atlanta airport. Each team was first tested using a scenario in which aircraft arrival times and positions at the sector boundary were identical to those on the sample day SAR tape in which the normal 20 MIT restriction was issued. The team then attempted the problem with the same air traffic arriving at the sector boundary at times corresponding to reduced restrictions of 15 MIT, 10 MIT, and a test with no restriction (minimum 5-mile separation).

Boundary arrival times, and aircraft sequences were calculated by a fast-time simulation of the aircraft queue at the departing runway (see section 4.8). In each case, the sequence was determined by the published gate departure times for aircraft that had intended to depart the runway on the historical sample day rush period. The total number of aircraft handled by the controllers during each of the first 4 test runs was 41 including Atlanta departures, Charlotte departures, and overflights. The total number of aircraft in the Atlanta departure queue during this period was 48, with 24 of those departing through sector 32.

The fifth test run duplicated the traffic with no MIT restriction. However, to simulate future increases in traffic demand, a 10-percent increase in the number of aircraft departing the runway at Atlanta were injected into the scenario. The additional aircraft were randomly assigned to depart to sector 32 or to depart to other en route sectors served by the runway, yielding a total of 53 aircraft in the queue, with 26 departing through sector 32.

Each controller team and its observing supervisor participated in a structured debriefing session after completing all five test runs. The debriefing was used to solicit comments from the group regarding the fidelity of the simulation, procedures used to control traffic during the test,

the perceived effectiveness of Data Link, and the Data Link human-computer interface.

4.5.3 Data Collection and Analysis.

The primary benefit measure that was calculated for experiment 1 was the difference between the ground delay times for departure aircraft under the 20 MIT restriction and those that would be experienced under the least restrictive test run that was safely completed during the Data Link simulation. The ground delays at each level of restriction were computed using components of the fast-time simulation model (see section 4.8).

Additional measures were collected during the simulation runs and extracted from the sample day SAR, TGF, and voice recording tapes to supplement and support the primary benefit calculations. Measures of the safety of ATC operations collected during the test runs were used as criteria to determine the validity of any performance benefits that were observed. Measures of aircraft throughput and other performance and efficiency variables were applied to the test and sample day SAR tapes and to voice recordings as local outcome measures. In experiment 1, these outcome measures were used to determine whether any ground delay benefit was supplemented by an improvement of in-flight efficiency. Since the criterion and outcome measures were used both in experiment 1 and experiment 2, they are described in detail in a separate section of this report (see section 4.7).

4.6 EXPERIMENT 2 -- ARRIVAL SECTOR.

4.6.1 Test Scenario.

The scenario for this experiment was based on a recent historical sample of air traffic derived from sector 09 (Tiroe) in area 5 of the Atlanta ARTCC (figure 3.). This en route sector controls airspace from 11,000 feet to FL 230. Its primary task is to sequence aircraft arriving at the Atlanta airport. In addition, sector 09 handles overflight traffic and departures. Arrivals enter the sector in multiple streams and must be sequenced to depart the sector in trail over a single fix (Tiroe) with jets at 14,000 feet and turboprops at 11,000 feet.

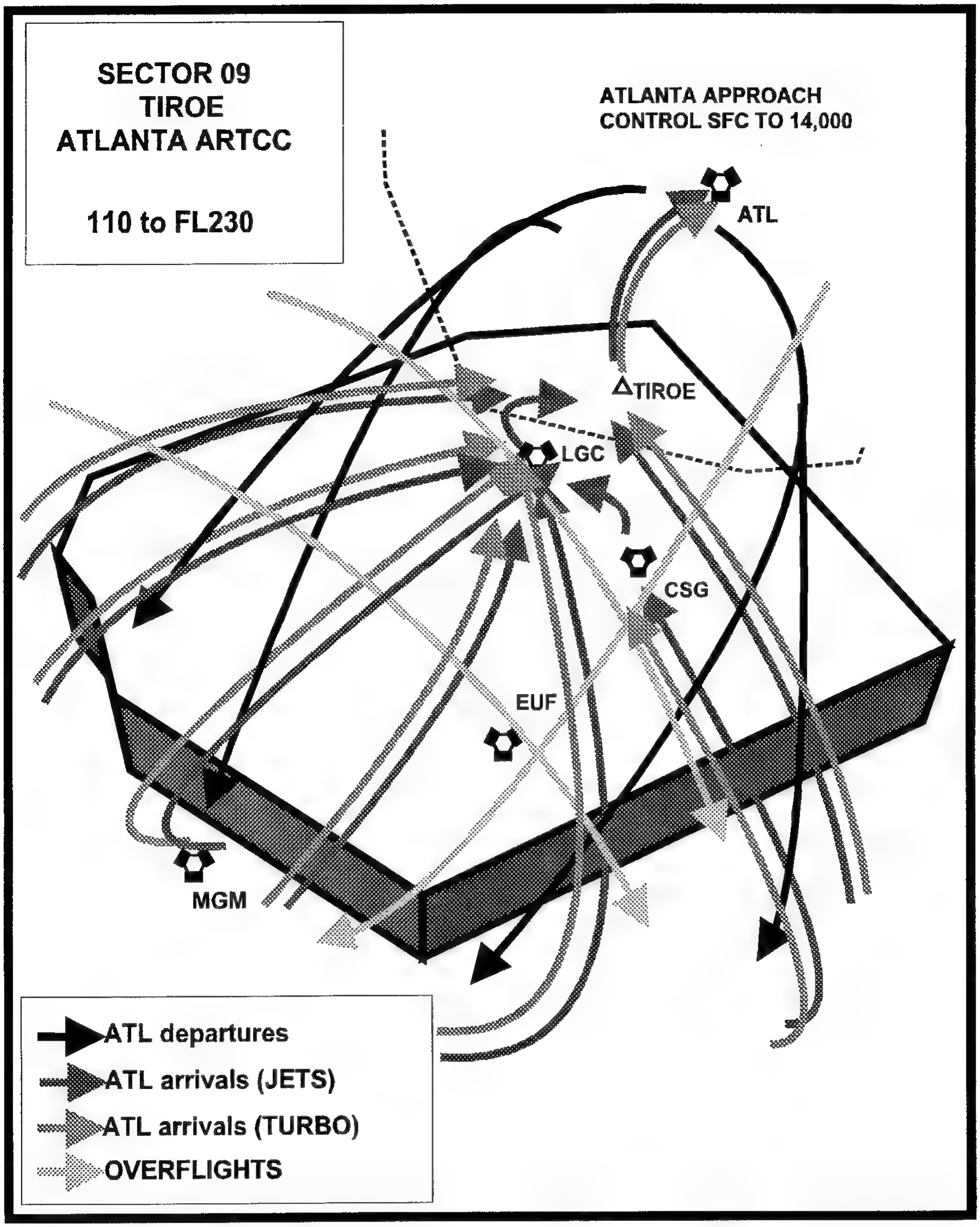

FIGURE 3. ARRIVAL SECTOR EXPERIMENT 2

From 8:00 a.m. to 11:00 a.m. and from 5:00 p.m. to 6:00 p.m. daily, traffic saturation in this sector typically creates a situation in which the controllers cannot achieve the specified MIT for aircraft exiting the sector for arrival at the Atlanta airport. The traffic volume often forces the use of a holding pattern and extensive use of vectoring. This situation delays arrivals at the airport and results in excess fuel usage. Experiment 2 was designed to determine whether the expansion of communications capabilities using Data Link at the sector would allow for more efficient traffic flow for arriving aircraft.

4.6.2 Testing Methodology.

Following the training and practice sessions, each team participated in five test sessions during which Data Link and voice radio were available for ATC communications. Each session consisted of a 1-hour period of ATC simulation. During the first test session, the team controlled traffic in a scenario which reproduced the arrival and overflight traffic demand recorded on the sample day morning rush period for sector 09 at the Atlanta ARTCC. A total of 40 aircraft were handled during the test scenario.

In the final four test runs, aircraft were added to the test scenario to provide an estimate of the team's capability to control sector 09 traffic at increased traffic demand levels. The added aircraft increased Atlanta arrival traffic demand by approximately 10 percent on the second run, 20 percent on third, 30 percent on the fourth, and 40 percent on the fifth. Specifically, Atlanta arrivals increased from 23 on the baseline day to 31 by the fifth test run, producing a final total count of 48 aircraft in the scenario.

In order to increase demand within the same time span used for the first test session, aircraft were added in gaps between arrivals at the test sector that were present on the sample day SAR tape. Because a restriction at an arrival fix is determined by the airport acceptance rate, the MIT restrictions for arrivals were not modified to accommodate the increased traffic test runs. All five test runs were conducted using the MIT restrictions over the arrival fix that were set by the Atlanta Traffic Management Unit during the historical baseline day rush period. These restrictions began at 15 MIT, were reduced to 10 MIT after the first 20 minutes of the sample period, and were completely removed during the final 10 minutes.

Each controller team and its observing supervisor participated in a structured debriefing session after completing all five test runs. The debriefing was used to solicit comments from the group regarding the fidelity of the simulation, procedures used to control traffic during the test, the perceived effectiveness of Data Link, and the Data Link human-computer interface.

4.6.3 Data Collection and Analysis.

The primary benefit assessment for experiment 2 was the efficiency with which the aircraft in the test scenario were passed through the arrival sector. Efficiency was measured using data extracted from the historical baseline SAR tape and from the SAR tapes generated during Data Link testing. The primary outcome measures included time in sector and distance flown for each aircraft (see section 4.7). A fast-time simulation model based on voice-only operational capabilities recorded on the historical SAR tape was used to generate baseline comparison data for the increased traffic test runs using Data Link. Additional measures were collected during the simulation runs and extracted from the sample day SAR and voice recording tapes to supplement and support the primary benefit calculations. Measures of the safety of ATC operations collected during the test runs were used as criteria to determine the validity of any performance benefits that were observed.

4.7 EXPERIMENTAL MEASURES.

4.7.1 Criterion Measures.

The measures discussed below were used in both experiments of this study to insure that any improvements in the efficiency of operations that yielded a user benefit were not achieved at any loss in system safety. Both primary indicators of safety and secondary or precursor indications of potential losses in the margin of safety were collected.

4.7.1.1 Primary Criterion Measures.

Three groups of measures were used as primary criteria for determining whether the ATC activities and aircraft operations observed during a test run were accomplished in a safe fashion. Failure to pass any one of the criteria resulted in rejection of the performance data for a test run. These measures were selected as primary criteria because they are essentially identical to

those currently used in the operational ATC environment to identify unsafe operating conditions and performance failures.

Aircraft Separation Violations and Causal Analysis

The TGF and Host computers continuously monitored aircraft separation during the test runs to detect violations of en route ATC separation minimums. Causal analysis of violations was possible through the use of TGF measures of the severity and duration of a violation as well as track plots of involved aircraft. According to procedures established for the study, test personnel, controller subjects and the observing supervisor were designated to make a group determination of the cause of any error. Potential causes included simulation pilot error, simulation equipment failure, software failure, or controller error. If the error were attributed to an equipment/software artifact or a pseudopilot error which affected the performance outcome, the test run would be repeated. However, if the separation violation was determined to have been caused by a controller error, the test run would be judged invalid.

Supervisory Safety Evaluation

When working in the en route ATC control room, area supervisors who are familiar with all aspects of sector operation monitor controller actions and air traffic activity to ensure operational safety. The supervisor uses expert judgment to make determinations of potentially unsafe conditions and to take measures to correct the problem.

This operational assessment technique was employed in the present study in the form of a comprehensive judgment for each test run. The supervisor accompanying each team indicated his judgment after observing the test run by completing the final item on the supervisory questionnaire (see appendix A). If a test run was judged unsafe, the supervisor was asked to record explanatory remarks.

Controller Safety Evaluation

In addition to supervisory monitoring, it is common practice in field ATC operations for controllers to identify potentially unsafe conditions that they encounter while staffing a sector. This evaluation was formalized for the present experiments using a comprehensive controller safety judgment corresponding to the overall supervisor's judgment. Following a test run, each controller on the participating team completed a safety evaluation (see

appendix A). If any of the team members judged the run as unsafe, they were asked to record explanatory remarks.

Pilot Safety Evaluation

Several aircraft in each test scenario were represented by high fidelity, piloted flight simulators. The professional aircrew flying these simulators were asked to provide a comprehensive evaluation of operational safety for each test run similar to those solicited from the supervisors and controllers (appendix A). Since the aircrew did not have access to a traffic display of the sectors during testing, this evaluation was based on the perceived accuracy and timeliness of communications with ATC.

4.7.1.2 Secondary Criterion Measures.

This group of measures included a number of indices that are believed to be capable of sensitively detecting controller states of high workload or task induced stress. Thus, they are indirect measures which may be potential precursors to safety related performance failures. While important, these measures were not used as criteria for accepting the validity of test run data since they did not indicate performance failures, in and of themselves. Instead they were intended as analytical aids for identifying potential changes in the margin of safety.

Handoff Offer/Accept Measures

Research on cognitive load suggests that operators performing complex tasks often respond to increasing task demands by sacrificing performance on secondary activities. The rationale for including the measures described below was that a busy controller may begin to shed task load by accepting handoffs later than normal, and/or by offering handoffs earlier, or later, than normal. Each of the parameters were measured objectively by analyzing the baseline day and test run SAR tapes to detect and record handoff offer and accept times for all aircraft in the scenarios.

The following measure was used to assess handoff acceptance by the controller teams:

Offer-Accept (O-A) Interval -- For aircraft entering the sector, the O-A interval was defined as the elapsed time from the sending sector's handoff offer keyboard entry to the receiving sector's handoff accept entry.

The following measures were used to assess handoff offers by the controller teams. In addition to identifying early handoff offers as a measure of load shedding, these measures were used in an attempt to capture late handoff offers that may have occurred because of inattention or perceptual overload.

Offer-Exit (O-E) Interval -- For aircraft leaving the sector, the O-E Interval was defined as the elapsed time from the offer of a handoff to the ghost controller to the time at which the aircraft crossed the exit boundary .

O-E Distance Flown -- For aircraft leaving the sector, the O-E Distance Flown was defined as the distance flown in tenths of miles during the O-E Interval.

Because these objective measures could be confounded in cases where handoff accept and offer times are not related to controller workload, a supervisory subjective rating also was used to assess the timeliness with which handoffs were offered and accepted (see below).

Supervisory Ratings of Workload/Performance Factors

Following each test run, the observing supervisors in these two experiments were probed on several factors believed to underlie their expert evaluations of workload in the field. Because of numerous mitigating factors, subjective evaluations were used to measure these variables with the supervisor acting as an "expert filter." In questions preceding the overall safety judgment on the questionnaire described in section 4.7.1.1, the supervisors were asked to judge the extent to which each of the following events occurred during the run:

Errors or Omissions in Required Flight Strip Marking

Descending Arrival Aircraft Early Rather than Permitting Fuel Efficient Descents

Climbing Departure Aircraft Late Rather than Permitting Fuel Efficient Climbs

Untimely Issuance of Clearance

Failure to Comply with Letters of Agreement

Early Handoff Offers

Late Handoff Offers

Delayed Handoff Acceptance

Failure to Meet MIT Restrictions

For each of the above, the questionnaire permitted the supervisor to indicate that the event (1) never occurred, (2) rarely occurred, (3) occurred, but within normal limits of operational acceptability, (4) occurred more often than normal for this sector at this time of day, or (5) occurred unacceptably often . They were also asked to comment on perceived causes for any negative judgment.

Controller Workload Ratings

Controller workload was assessed using a perceived subjective workload rating scale. Following each test run, each controller on a team was asked to rate the previous work period in comparison to a corresponding work period at their position in the sector at the Atlanta ARTCC. The test run workload could be rated as (1) much lower than usual, (2) somewhat lower than usual, (3) about the same, (4) somewhat higher than usual, or (5) much higher than usual.

4.7.2 Outcome Measures.

This class of measures was used to assess variations in operating efficiency for aircraft in flight. In the arrival experiment (experiment 2), these measures were the primary focus of the benefit assessment. In the case of departures (experiment 1), these measures did not assess the target benefit of decreasing ground delays, but were collected to identify any collateral in-flight benefit that may have been associated with the use of Data Link.

4.7.2.1 Primary Outcome Measures.

Primary outcome measures were acquired by direct analysis of the baseline and test SAR tapes. In each case, they were used to assess the overall efficiency with which aircraft operated within the test airspace in terms of time, distance traveled, and related resource usage.

Time in Sector and Distance Flown

For the following measures, sector entry and exit points were defined in

terms of the horizontal and vertical boundaries of each test sector. If an aircraft penetrated the sector airspace after crossing the horizontal boundary, the entry point was defined as the point at which it entered the sector's altitude limits. If the aircraft departed the sector airspace before crossing the horizontal boundary, the exit point was defined as the point at which it exited the sector's altitude limits.

Aircraft Time In Sector -- For each target aircraft, the elapsed time in seconds was recorded from entry to the sector to exit from the sector.

Aircraft Distance Flown in Sector -- For each aircraft, the distance flown in miles was recorded from the sector entry point to the exit point.

Problem Exit Time

The problem exit time measure was used to obtain an overall assessment of the efficiency with which the aircraft in the scenarios traversed the test airspace. Problem exit time was defined as the clock time at which each aircraft crossed a position in space which marked the logical termination of the ATC problem that was studied in the two experiments. This measure was obtained for the original sample day data, and for each Data Link test run.

In experiment 1, the aircraft entered sector 32 in two departure streams and diverged within the sector on routes to their destinations. For these aircraft, the problem exit time was defined as the clock time at which each aircraft departed the sector altitude or horizontal boundary.

In experiment 2, all arriving aircraft routes converged at a fix in sector 09 (Tiroe) and formed a stream of traffic for entrance to the terminal airspace. For these aircraft, the problem exit time was defined as the clock time at which each aircraft crossed the Tiroe fix.

Since problem start times were identical for the sample day and the initial test runs, comparisons of problem exit times were used to assess differences in the effectiveness with which the total air traffic sample departed Atlanta (experiment 1) and were delivered to the arrival fix (experiment 2).

Analysis of Flight Path Records

The time and distance measures discussed above could not reveal control strategies that were used to achieve specific time and distance results. For this reason, data visualization tools were applied to the SAR tapes to produce

horizontal and vertical profile tracks for the test runs and for the baseline days. These plots were used to detect shortcut paths used by controllers , holding patterns and vectoring, and descent and climb profiles that were relatively more or less efficient.

Fuel Consumption

Fuel consumption computations are strongly affected by preferred flight profiles and unique aircraft equipment features that differ among commercial carriers. Because of this, the present experiment focused on flight time and distance metrics to assess efficiency. However, to provide some indication of how these findings translated to resource usage, sample fuel burn data were computed for selected aircraft in experiment 2 which were represented by piloted, full fidelity flight simulators and their counterpart aircraft represented on the sample day SAR tapes. The estimates for the test runs were calculated by fuel consumption models associated with the piloted simulators. Estimates for the historical baseline day flights were obtained from additional off line runs in which the simulators flew profiles that duplicated those of their counterpart aircraft on the historical SAR tapes.

4.7.2.2 Secondary Outcome Measures.

As in the criterion measures category, in addition to direct measures of performance, indicators of precursors to the benefit measures of interest were collected as a secondary outcome indicator. This study was based on the premise that adding Data Link to the existing voice radio would expand the control team's communications capacity, thereby permitting them to more efficiently handle aircraft in sectors saturated because of communications problems. Thus, any benefit that was measured should have been correlated with a redistribution of ATC communications among the two channels. The following measures were used to determine the manner in which the test controllers used Data Link and voice to accomplish their communications tasks.

Number, Duration and Content of Voice Messages

The frequency with which the test controllers and simulation pilots used the voice radio channel was measured by counting the number of messages contained in transcripts of the voice recordings made during the test runs and those obtained from the Atlanta ARTCC for the historical baseline days. The time spent by the controllers and simulation pilots communicating on the

voice channel was measured by manual timing of the messages on the test and sample day audio recordings.

The content of the voice messages sent by controllers during the test runs and on the sample days also was assessed by reviewing the voice tape transcripts. Messages were tabulated by message category. These categories included: (1) individual speed, heading and altitude clearances; (2) combined clearances (3) transfer of communication messages; (4) responses to initial contact calls; (5) informational messages; (6) route changes; and other messages, as required.

Number and Content of Data Link Uplinks Sent

The number and content of Data Link messages sent by controllers were assessed by analyzing the SAR tapes from the test runs. Messages were tabulated by message category. These categories included: (1) individual speed, heading and altitude clearances; (2) combined clearances; (3) transfer of communication messages; (4) informational messages; (5) route changes; and other messages, as required.

4.7.3 Subsidiary Measures.

Two additional measures were used to meet subsidiary human factors objectives of this study. Following each test run, supervisors at each sector were asked to report on errors in Data Link keyboard inputs. If any errors were observed, the supervisors were asked to describe how the errors were resolved. They also made a projective evaluation of the potential for occurrence of undetected Data Link errors in a field implementation (see appendix A).

In order to obtain information on how sector tasking and communications were distributed among the sector personnel, each controller on a team completed a duty profile after each test run. The profile required the controllers to rate the frequency with which they performed 13 sector tasks during the previous test run (see appendix A).

4.8 FAST-TIME SIMULATION.

A fast-time simulation was employed to supplement and support the real-time, controller-in-the-loop testing methodology used in this study. This section describes the modeling tool that was used to perform the fast-time simulation and presents a summary of its applications to the two experiments.

4.8.1 SIMMOD Description.

SIMMOD is an airport and airspace computer simulation model. Since 1978, SIMMOD's development has been supported by the FAA as an operations research tool. Its purpose is to test proposed improvements in facilities, procedures, and technologies, and to assess the impact of projected growth on air and ground operations.

SIMMOD is a network model in which points in space are defined as network nodes, and links represent routes connecting the nodes. Using this form of representation, SIMMOD can track the simultaneous movement of individual aircraft from pushback and taxi, to take-off, flight, and arrival. Based on time and fuel burn calculations, it can produce a wide range of data on travel time, delay, and economic impact.

The simulation logic of SIMMOD is described as "event-stepped." Each aircraft movement is checked against other possible conflicting aircraft in the problem before that aircraft is allowed to proceed. The airborne portion of the model maintains sector capacities and minimum in trail separations by simulating air traffic decisions to vector, speed up, slow down or hold aircraft. The simulation's look ahead capability permits realistic sequencing of traffic at merger points, balancing of en route flow, and resetting of restrictions.

As with other modeling techniques, the accuracy and validity of a SIMMOD application depend upon the data inputs that it receives. Building a SIMMOD model to analyze operational costs associated with a particular air traffic scenario requires three basic input files. The airspace file defines the route structures and governing airspace procedures for the section of airspace to be simulated. The airport file defines the structure of any runways, taxiways and gates required by the model. The event file contains the schedule of flight operations for the aircraft participating in the scenario.

For the present study, SIMMOD was used in a selective fashion to address specific questions about the impact of Data Link on flight departure delays and on sector throughput in the Atlanta ARTCC sectors tested during the experiments (LeTech, 1995). In all cases, the basic inputs to the model were derived from the historical SAR tapes for the sample days in the two sectors.

4.8.2 Experiment 1 Calculations.

SIMMOD supported experiment 1 by providing both test scenario design inputs and benefit calculations. Initially, SIMMOD was used to determine

sector 32 entry times under the MIT restrictions that were tested in the experiment. A SIMMOD model was developed to define the sector entry time for each departing aircraft recorded on the historical sample day SAR tape in which a 20 MIT restriction had been implemented. This model was validated by comparison of the model outputs to data taken directly from the SAR tape. Model parameter adjustments were made to maximize comparability of the output to the historical data. SIMMOD then was used to generate sector entry times for each aircraft under the 15 MIT restriction, 10 MIT restriction, and no restriction cases. These outputs were used to create scenario demand files for the Data Link simulation runs in experiment 1.

The primary application of SIMMOD in the departure experiment was the calculation of benefits. Ground delay for the 20 MIT base case was computed by subtracting the scheduled departure time for each aircraft from the actual take off time generated by the validated model. Scheduled gate departure times (P times) were obtained from the P times recorded on the historical SAR tape. Ground delays were then computed for the 15 MIT, 10 MIT and no restrictions cases. The ground delays began to accumulate as each aircraft reached the departure queue, and did not include normal push back and taxi times. In computing these delays, the model imposed the relevant restriction only on aircraft departing for sector 32. However, the delay estimates included the effects that the restrictions have on all aircraft departing the same runway during the sample period. That is, the total delay calculation included the impact on aircraft entering sector 32, and on those whose take off times were affected by the restricted aircraft. The net benefit was computed by comparing the total aircraft delays under the 20 MIT restriction and the minimum level of restriction under which the subject controllers were able to safely control traffic during the manned simulation testing.

SIMMOD also was used to assess the impact on total delays of increasing the departure traffic demand. The number of departing aircraft were increased by 10 percent, and the model was run with the historical 20 MIT restriction to calculate baseline delays. The model was then run with no departure restrictions and the 10-percent traffic increase. The delay difference between the two runs was used as the benefit estimate if the subject controllers were able to safely control the increased traffic with no restrictions using the combined Data Link and voice radio communications during manned simulation.

4.8.3 Experiment 2 Calculations.

The basic test for experiment 2 compared the flow of traffic on the historical

sample day to that obtained under Data Link communication conditions in the real-time simulation. This test was completed by direct extraction of outcome measures from the original and experimental SAR tapes. To support additional benefit calculations, SIMMOD was used to provide estimates of sector 09 throughput and operating efficiency under voice radio-only conditions with traffic levels increased from those experienced on the sample day. This output was compared to live simulation data obtained when subject controllers using a combined Data Link and voice radio system attempted to cope with additional increases in traffic volume.

A SIMMOD model of sector 09 was first constructed to emulate the traffic flow and operating efficiencies which characterized the performance recorded on the historical SAR tape. The Atlanta arrival traffic demand at the sector 09 boundary was then increased on successive model runs by 10, 20, 30, and 40 percent to provide estimates of the throughput and efficiency that would be demonstrated if the sector were challenged by these demands using current, voice-only communications. The output was compared to the data produced by live simulation with Data Link when traffic in the test scenarios was increased in identical increments.

5. RESULTS.

5.1 EXPERIMENT 1 -- DEPARTURE SECTOR.

As described in section 4, the primary user benefit of Data Link communications hypothesized for experiment 1 was a reduction in ground delay for aircraft awaiting departure from the runway serving sector 32. The magnitude of this benefit depended on whether the test controllers could safely accept and control the increased traffic density that would occur as the MIT restrictions were reduced on departures entering the sector. The following subsections first present data on the criterion safety measures that were collected on each of the five test runs completed by the three teams of sector 32 controllers. Ground delay data are then presented which correspond to the MIT restrictions at which test runs were safely accomplished by the subjects.

5.1.1 Criterion Performance.

5.1.1.1 Aircraft Separation.

Aircraft separation was continuously monitored at the Host operator's console during each test run. No operational errors (minimum en route

separation violations) were recorded between aircraft in sector 32 on any of the five test runs for any of the three teams of controllers.

5.1.1.2 Operational Safety Assessments.

Controller and Supervisor Ratings

Expert operational assessments of the safety with which the test runs were completed are shown in figure 4. The histogram presents the frequency with which the 15 test runs (five per team) received each of the four possible safety ratings from the radar, data and tracker controllers as well as the observing supervisor for the sector.

As shown in the figure, none of the controllers or supervisors rated any of the test runs as "unsafe." Supervisors assigned the test runs the highest ratings with 11 runs rated as having a greater margin of safety than normal for the sector in the operational voice-only environment, and four runs rated as having typical levels of safety. The controllers rated the safety of a majority of the test runs as typical for the sector during the rush period (31 of 45 ratings). Eleven runs were rated as having a higher margin of safety than normal.

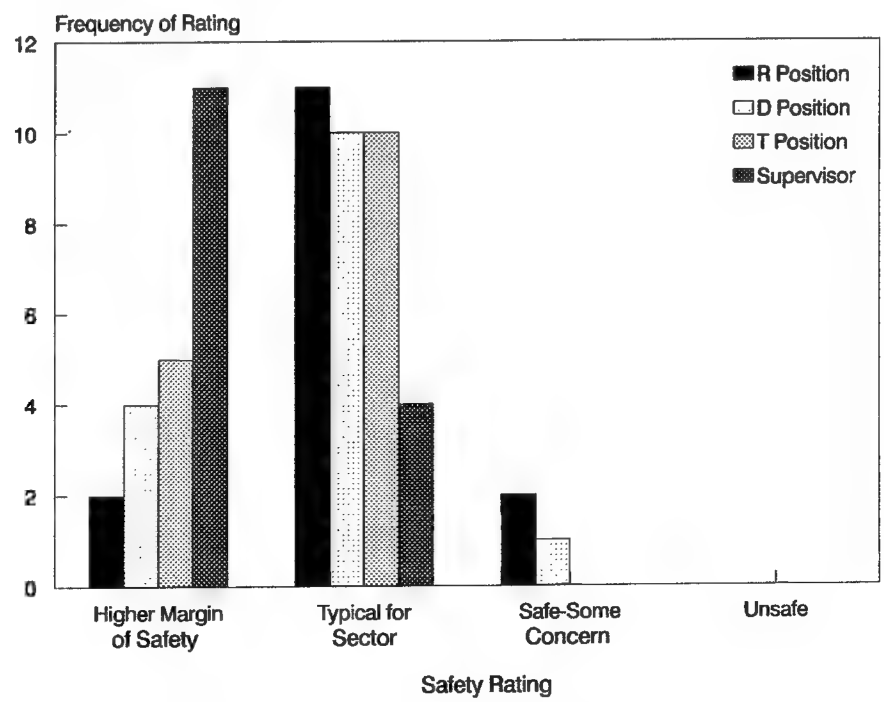

FIGURE 4. SECTOR 32 SAFETY RATINGS

Three of the 45 controller ratings were in the category "safe, but some concern." Two of these ratings were assigned by the same radar controller to runs one and two (20 and 15 MIT). The third was assigned by a data controller on run two (15 MIT). Comments written by these personnel indicated that they felt that safety had not been compromised during either of the two initial test runs. Although no input error occurred, they expressed some concern over the possibility that a keyboard error could have caused a separation violation. Both controllers rated safety on the three remaining, higher difficulty test runs as typical for the sector.

Further examination of the ratings across test runs revealed no evidence for a reduction in perceived safety as a function of the complexity of the control problem. On the 1 (higher margin of safety) to 4 (unsafe) scale, average team ratings for the three groups of controllers and supervisors were 1.83 for both the baseline 20 MIT and 15 MIT spacings, 1.75 for the 10 MIT spacing, and 1.5 for both the unrestricted run with baseline traffic levels and the unrestricted run in which departure traffic was increased by 10 percent.

<u>Pilot Ratings</u>

Pilot safety assessments were performed as part of a post run questionnaire completed by the two pilots who flew each full fidelity flight simulator during the test runs, and by simulation site coordinators who acted as observers. They rated the flights on a scale ranging from "completely safe" (1) to "completely unsafe" (7). The FAA RCS configured as a B747, the Avia 727, and the NASA B747 participated in all sector 32 flights. The FAA and Avia simulators were equipped to receive Data Link. The NASA simulator was able to communicate using voice radio only.

On each test run, the FAA and Avia simulators completed one flight, while the NASA simulator completed two flights. Thus, observer, pilot flying (PF) and pilot not flying (PNF) safety ratings were obtained on four flights for each of five test runs. Over the three replications of the experiment, this produced a total of 60 safety rating opportunities.

For the purpose of analysis, the three ratings for each flight were summed to produce a scale with a minimum value of 3 (completely safe) to 21 (completely unsafe). Of the 60 flights, 49 (82 percent) received combined ratings of 3, indicating unanimous agreement among the raters that the flight had been completely safe. The remaining 11 flights all received

ratings below the midpoint of the combined safety scale (12), with 7 of these flights receiving combined ratings of 4 or 5.

The poorest individual ratings were assigned to 2 of the 60 flights. On one flight during run 5 of the experiment, the PNF assigned a rating of 6 on the 1 to 7 scale. The PF and observer assigned the flight a 2 and 3, respectively. Written comments from all three raters indicated that the perceived reduction in safety was attributable to a failure of the simulated Data Link avionics. Both pilots noted that the computer display unit (CDU) that was used to display messages and enter responses would not accept message confirmation (wilco) entries, and that it had presented numerous error messages.

On a second flight during run 4, the PNF's rating was 5, while the PF and the observer each rated the flight as "completely safe" (1). The PNF's comments indicated that he felt that he had missed a Data Link message after receiving a radio inquiry from the controller regarding his failure to respond to an altitude clearance. The observer's comments indicated that the PNF had, in fact, responded to the Data Link clearance, but that the system had failed to return the response to the controller. The observer explained that it had been the PNF's first test run, and that he had been confused about the meaning of an error message from the simulated Data Link equipment which had signaled the failure of the downlink attempt.

The incidents described above suggest that the poor safety ratings for 2 of the 60 cases were caused by local simulation equipment failures. Since neither rating was attributable to controller error or to inherent problems with Data Link ATC communications, the associated test runs were not judged invalid.

5.1.2 Ground Delay.

The results discussed in section 5.1.1 demonstrate that the control teams in all three replications of the experiment were able to safely control the air traffic at all reduced spacing restrictions. These included the conditions in which air traffic demands were increased and aircraft were permitted to arrive at the sector with the legal minimum 5-mile spacing. Ground delay reductions associated with the performance achieved by the control teams using Data Link are presented below.

SIMMOD airport calculations were performed for all four spacing restrictions tested during the study in order to compute the ground delays.

Total delay for the 48 aircraft departing the runway serving sector 32 under the 20 MIT restriction that was in force during the sample day rush period was 1,795 minutes, or an average of 37.4 minutes per aircraft. Reductions in total ground delays for the same aircraft sample when the use of Data Link permitted the relaxation of restrictions are illustrated in figure 5.

Because the controllers in the present experiment were able to reliably and safely control the baseline traffic sample with the minimum 5-mile spacing, the maximum reduction in delay shown in the figure was achieved. The 687 minutes of delay with no restriction in force represents an average reduction of 23.1 minutes per aircraft (62 percent) in ground time from the daily 20 MIT restriction that is currently issued at the Atlanta ARTCC using voice-only communications.

Figure 5 also presents the results of SIMMOD ground delay calculations when aircraft in the queue to depart the runway serving sector 32 were

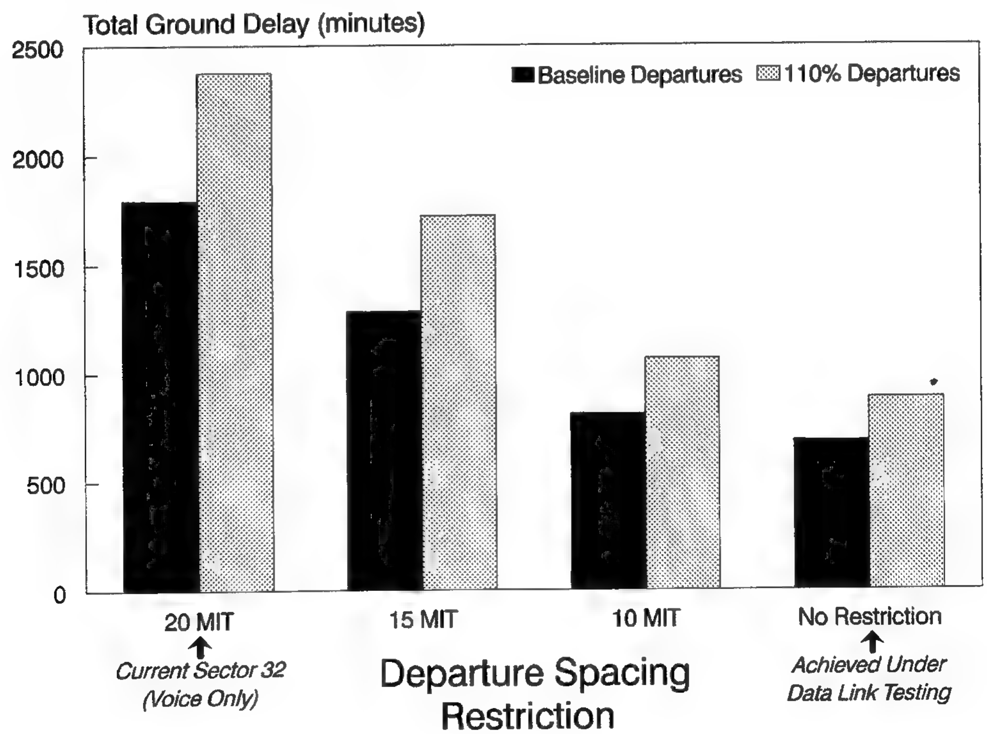

FIGURE 5. ATLANTA DEPARTURE GROUND DELAY SAVINGS

increased by 10 percent. As shown in the figure, in comparison to the baseline traffic, the increase in departure runway demand increased total delay under all restrictions. However, the absolute magnitude of the increase in delay diminished with the reduction in MIT restrictions. Under the 20 MIT restriction normally enforced for sector 32, a 10-percent growth in departures increased total delay by 582 minutes. However, at the minimum 5-mile spacing that was successfully tested using Data Link, the total delay increased by only 197 minutes.

Taken together, the results suggest that, if Data Link were implemented to eliminate the current 20 MIT restriction, there would be a major reduction in average, per aircraft ground delay under present demand conditions. Furthermore, while future increases in demand under the current 20 MIT restriction would result in a rapidly accelerating increase in ground delays at Atlanta, they would be accommodated with a much slower growth in total delay in the unrestricted departure environment made possible by Data Link ATC communications. Estimates of the economic benefits associated with the ground delay savings are presented in section 6 of this report.

5.1.3 Sector Throughput.

While the primary focus of this experiment was Data Link's impact on ground delays, measures of in-flight performance also were collected. The goals of the following analyses were to (1) determine whether Data Link provided any collateral in-flight benefit, and (2) ensure that any ground delay reduction was not compromised by a loss in the efficiency with which aircraft were controlled in the test sector.

Figures 6 and 7 present the mean aircraft flight time and distance flown in sector 32. The data shown in the graphs for the voice-only condition were derived directly from the sample day SAR tape. Data for Data Link testing are averages across the three test control teams. All aircraft that flew in the sector during the sample period are represented in the graphs including Atlanta departures, Charlotte departures, and overflights.

As shown in the figures, the addition of Data Link communications was associated with a reduction in mean aircraft flight time and distance over all test conditions. The average aircraft on the historical baseline day flew 52 miles in the sector over almost 7 minutes. Collapsing across all restrictions and traffic levels, mean flight distance was reduced to 40 miles over 5.5 minutes during Data Link testing.

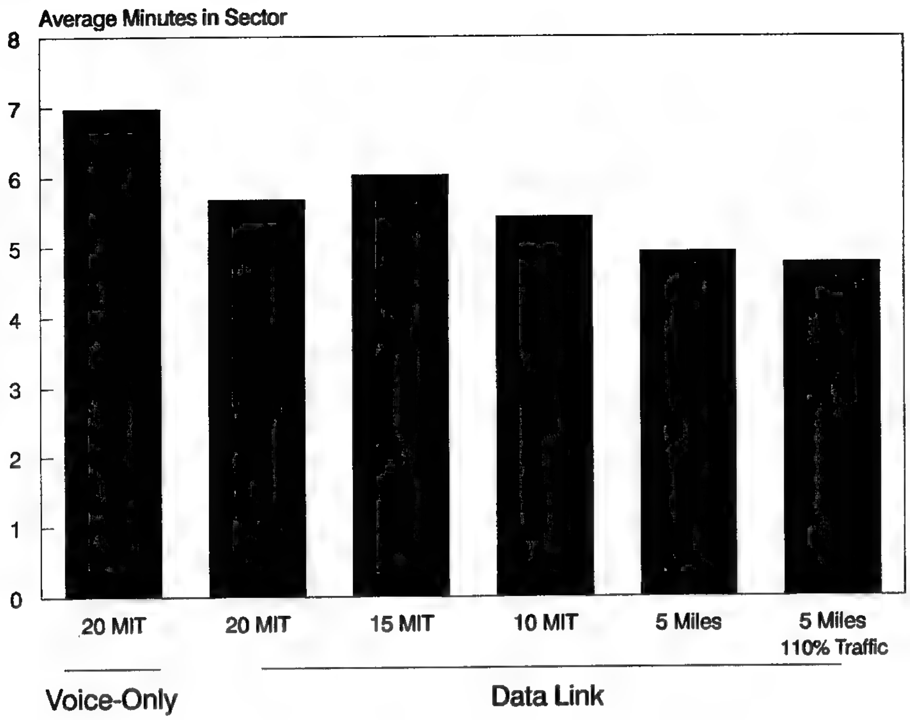

FIGURE 6. AVERAGE AIRCRAFT TIME IN SECTOR 32

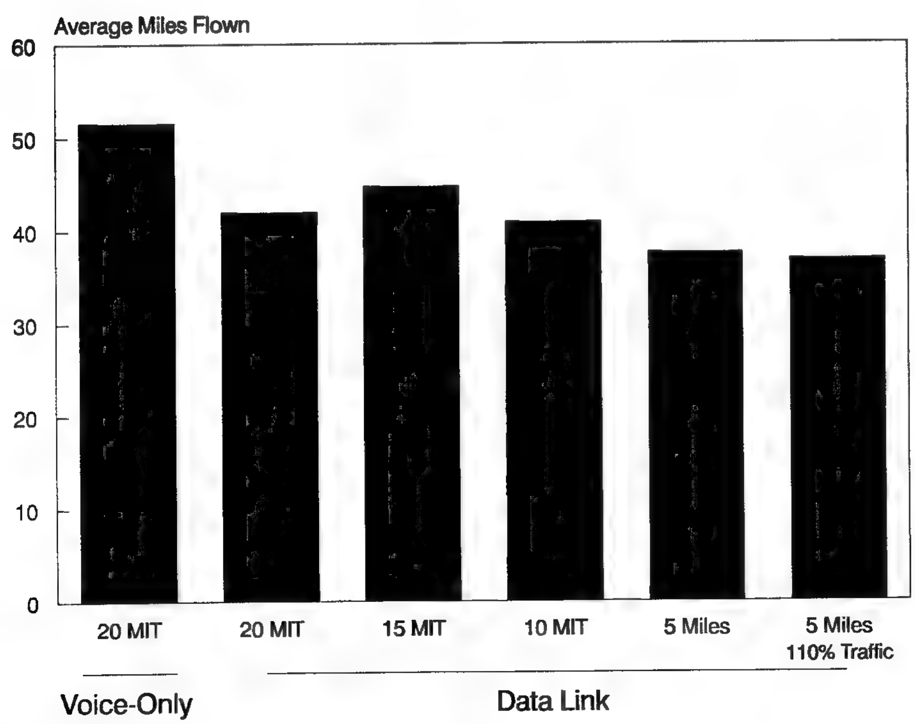

FIGURE 7. AVERAGE AIRCRAFT DISTANCE FLOWN IN SECTOR 32

In examining these data, it should be noted that the flight time and distance measures are closely correlated. This suggests that the controller teams did not use potentially inefficient speed increases to reduce time in sector. However, evaluation of sample flight track profiles from the baseline Atlanta data and the test trials did reveal one identifiable source of the observed improvement in sector throughput.

While no general differences in control strategy were observed, the Atlanta departure traffic appeared to be handled differently on the baseline day and in the test runs. Specifically, departures climbing into the sector on the baseline day when only voice communications were available tended to be held at altitudes within the sector boundaries for a longer period time before departing the ceiling for their desired cruise altitudes. During Data Link testing, it appeared that controllers were able to release these aircraft to the higher altitudes sooner, resulting in shorter sector flight times and distances.

Comparison of the data from individual test conditions in figures 6 and 7 also demonstrates that the in-flight benefits discussed above were not a result of the reduced MIT restrictions that were employed during testing. While the final four test runs were completed under different traffic density patterns for arrival at the sector boundary, the first run precisely duplicated the pattern of traffic produced by the 20 MIT restriction on the historical sample day. Thus, the time and distance data for the first run are directly comparable to the baseline day. Both of these average in-flight measures for the first test run show an improvement over the baseline day.

Figure 8 breaks out the flight time and distance means for the three categories of air traffic that flew in sector 32 under the 20 MIT restriction. As shown in the figure, the Atlanta departures, which represented the primary traffic flow during the rush period, reflect the overall improvement in efficiency shown in the combined comparison of the voice-only baseline and the Data Link test data. In addition, similar reductions are apparent for the Charlotte departures and overflight aircraft handled by the sector. Thus, the results indicate that improvements in the primary traffic flow in the sector were not achieved by sacrificing service to other aircraft.

Traditional statistical analysis of the significance of the results of the throughput measures were not warranted because of the relatively low

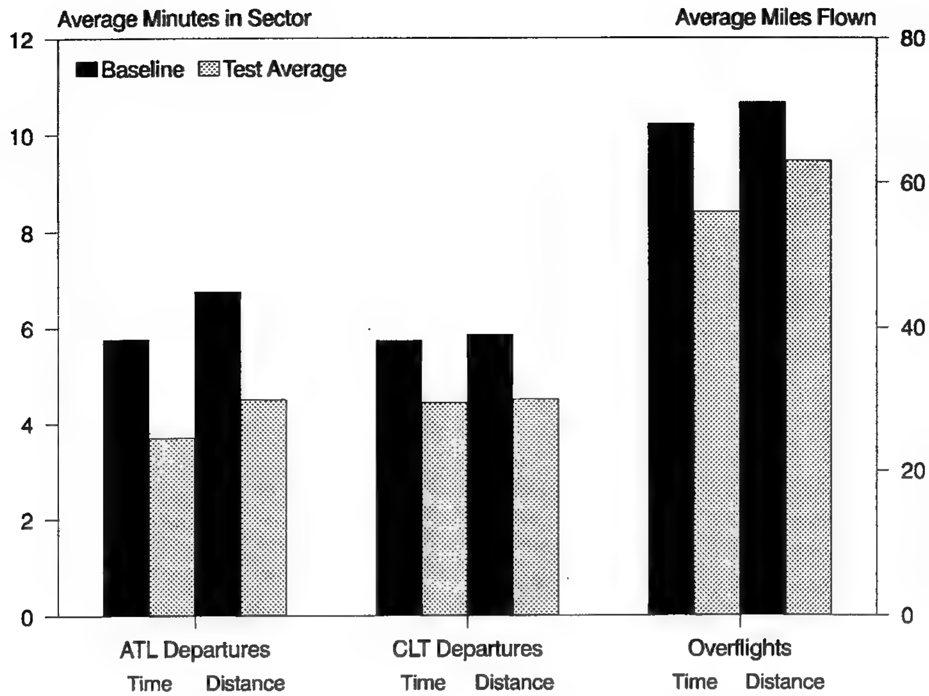

FIGURE 8. TIME AND DISTANCE FLOWN IN SECTOR 32 BY ATLANTA DEPARTURES, CHARLOTTE DEPARTURES, AND OVERFLIGHTS

number of control teams that could be practically tested. However, since the three teams represent a reasonably large sample of all controllers from Area 2 of the Atlanta ARTCC, the reliability of the findings can be inferred by examining the repeatability of the outcome across the three independent test teams. Figure 9 displays the flight time and distance data averaged across all test runs for each of the control teams that participated in the experiment. As shown in the figure, all three teams displayed improved efficiency during testing with the Data Link system in comparison to their counterparts using only voice radio on a typical day at the operational facility.

An alternative statistical analysis of the data was conducted by treating the individual Atlanta departure aircraft as subjects, and comparing each aircraft's flight efficiency on the baseline day to its performance under the three test teams' control for the 20 MIT condition. The repeated measures analysis of variance indicated that departure performance with Data Link was significantly better than that on the baseline day under voice-only communications ($F_{18,57} = 8.68$, $p<.01$).

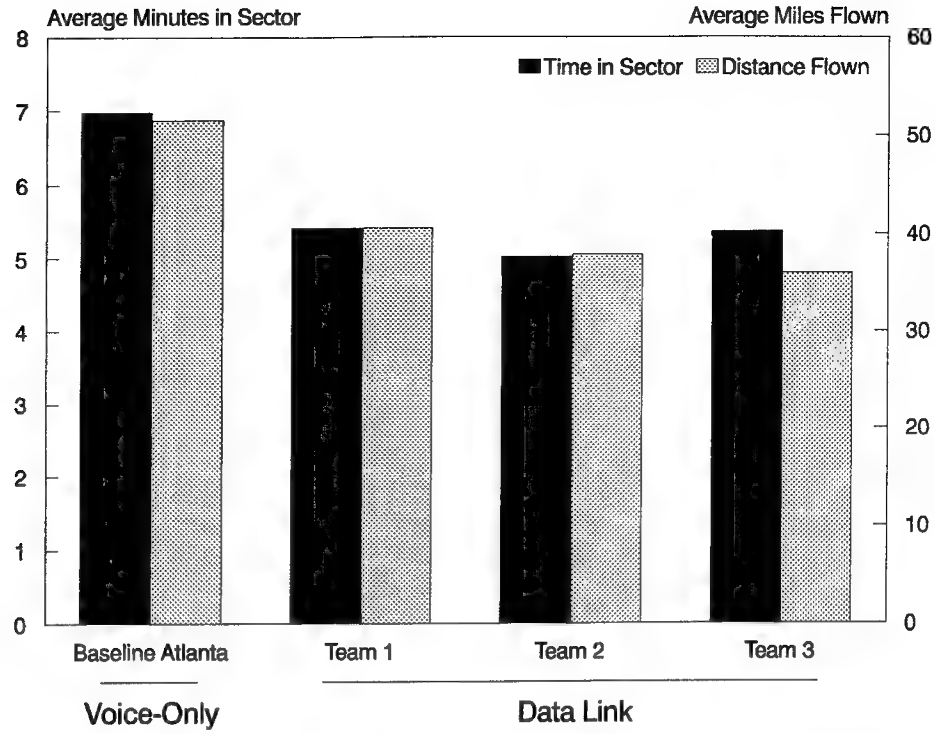

FIGURE 9. TIME AND DISTANCE IN SECTOR FOR THE THREE SECTOR 32 TEAMS

Figure 10 presents a final portrayal of the in-flight efficiency data. The histogram shows the processing time for all Atlanta departure aircraft averaged across teams for each test condition. Processing time was calculated for the baseline day and the test conditions by subtracting the problem exit time for the first Atlanta departure aircraft leaving sector 32 from that of the last aircraft. Thus, processing time reflects time needed to complete the sector's task of controlling the entire departure traffic sample during the rush period in order to place the aircraft on their destination routes at the boundaries.

This view of the data demonstrates that the ground delay savings obtained at each reduced MIT restriction made possible by Data Link communications were not only preserved as the aircraft departed the sector, but were supplemented by the enhanced in-flight operational efficiency. As shown in the figure, 47 minutes were needed to process all of the departures on the historical baseline day using voice-only communications. Under testing where the communications channel was expanded by Data Link, processing time was reduced by an average of 16.6 minutes (35 percent) at the minimum spacing for the same traffic

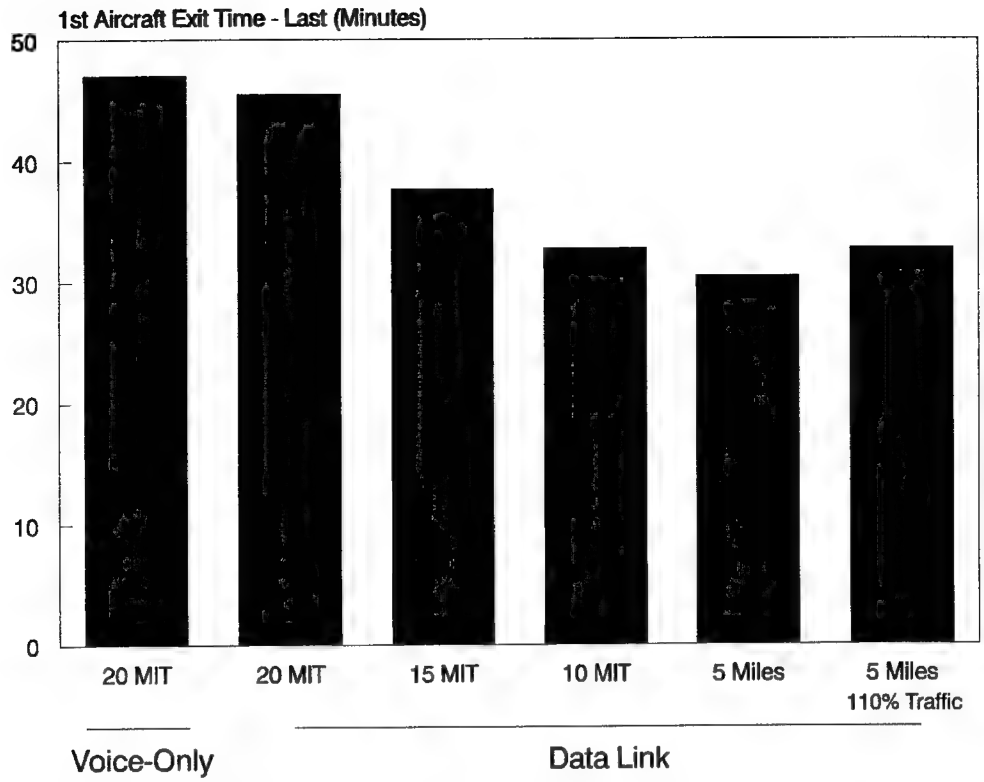

FIGURE 10. DEPARTURE TRAFFIC PROCESSING TIME IN SECTOR 32

sample. The data also show that departure processing time was shorter even when the aircraft were subjected to the same 20 MIT restriction as that imposed on the baseline day (45.5 minutes), and when two additional aircraft were added to the traffic sample with minimum spacing (32.8 minutes).

Section 6 presents estimates of the economic benefits associated with the in-flight efficiency improvements discussed above, along with those provided by the ground delay savings obtained in this experiment.

5.1.4 Secondary Criterion Measures.

As described in section 4, operational safety measures were used as criteria for validating the NAS user benefits identified during testing. The findings discussed in this section were obtained using a group of measures intended to determine whether these benefits were achieved at any expense to the general quality of task performance exhibited by the controllers or any increase in the workload levels that they experienced.

5.1.4.1 Supervisor Performance Ratings.

During each test run, the supervisors were asked to judge the control team on nine factors indicative of degraded sector performance. A 5-point rating scale ranging from 1 "never occurred" to 5 "occurred unacceptably often" was used to quantify the judgments.

Ratings on each dimension for the five test conditions averaged across the three supervisors are summarized in figure 11. None of the average ratings exceeded the midpoint on the scale (3 - "within normal limits for the sector during this duty period"). Although flight progress strip marking appeared to receive the poorest average ratings overall, none of these indicated that omissions or errors were greater than normal for the sector during the duty period under examination in the experiment. Inspection of the data for individual teams indicated that all of the five ratings of the nine factors made by each supervisor were "within normal limits," or better. As shown in the figure, the mean ratings also did not

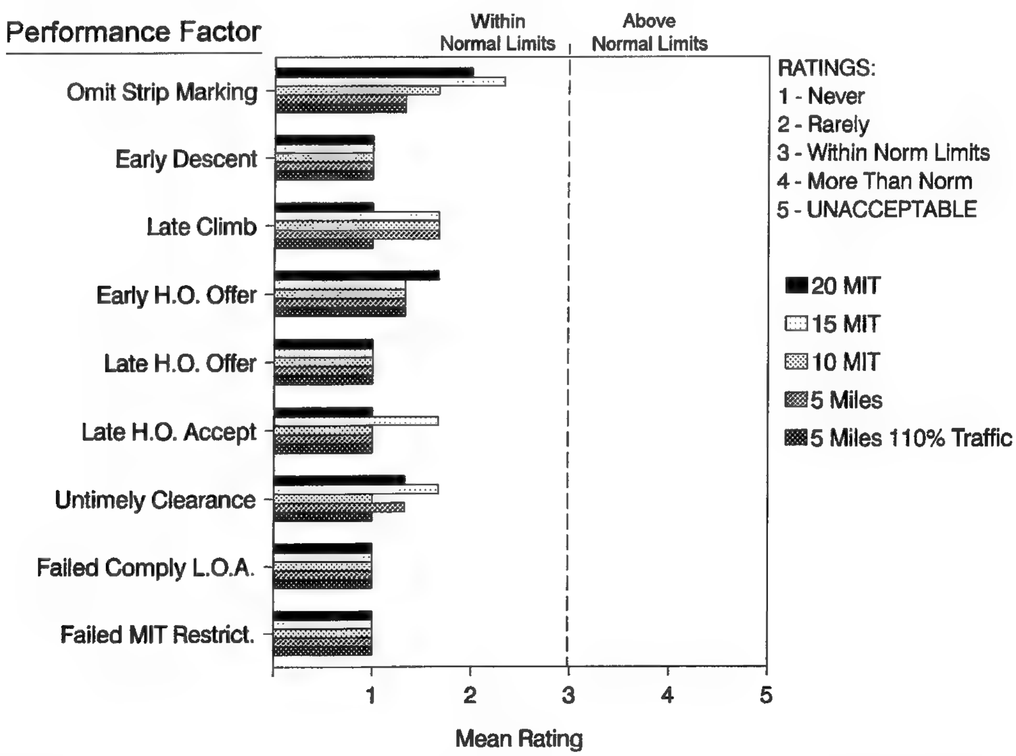

FIGURE 11. SECTOR 32 SUPERVISOR RATINGS OF CONTROLLER PERFORMANCE

reveal any tendency for deterioration in sector performance as the MIT restrictions were reduced or traffic was increased.

5.1.4.2 Controller Workload.

Controller workload was assessed using a subjective rating scale of perceived effort. Following each test run, the controllers rated their workload on a 5-point scale relative to their normal workload at sector 32 for the same work period. Figure 12 presents the mean workload ratings for each control position across the five test runs.

As indicated by the figure, the mean ratings for all test runs and control positions were below the midpoint rating of 3 ("about the same"). In addition, there was no apparent trend for average workload ratings to increase when the MIT restrictions were reduced or when the traffic demand increased by two aircraft.

None of the individual subjects assigned a workload rating of 5 - "much higher than normal" to any of the test runs. "Somewhat higher than normal" (4) ratings were received by the 15 MIT test run from the radar, data and tracker positions on one team, and by the no restriction and 110

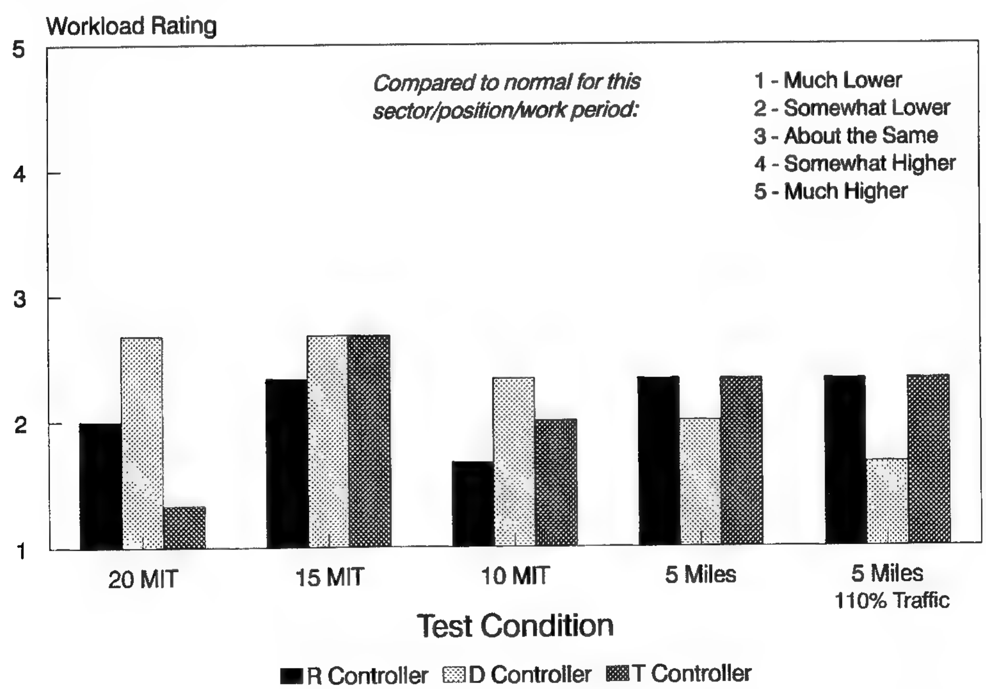

FIGURE 12. SECTOR 32 CONTROLLER WORKLOAD RATINGS

percent traffic runs from the radar position on another team. Overall however, of the 45 individual measures obtained over all test runs and teams, 26 ratings indicated that workload was "much lower" or "somewhat lower" than normal, and 14 ratings indicated that position workload was "about the same" as normal for the sector during the tested work period.

5.1.4.3 Handoff Measures.

Measures of controller performance in accepting handoffs from, and offering handoffs to, adjacent sectors were collected during the experiment as subsidiary workload indices. Figure 13 presents results for two handoff measures obtained from the baseline Atlanta SAR tape and the comparable 20 MIT test run with Data Link. As discussed below, both measures were in agreement with the subjective ratings, indicating no significant change in controller workload under Data Link testing.

The O-A Interval is an index of the average time taken by the control team to accept an aircraft handoff from a sending sector. It was hypothesized that increased workload may have been reflected by delays in accepting the offer. As shown in figure 13, no evidence of an increase in controller workload during Data Link testing was provided by this measure. In fact,

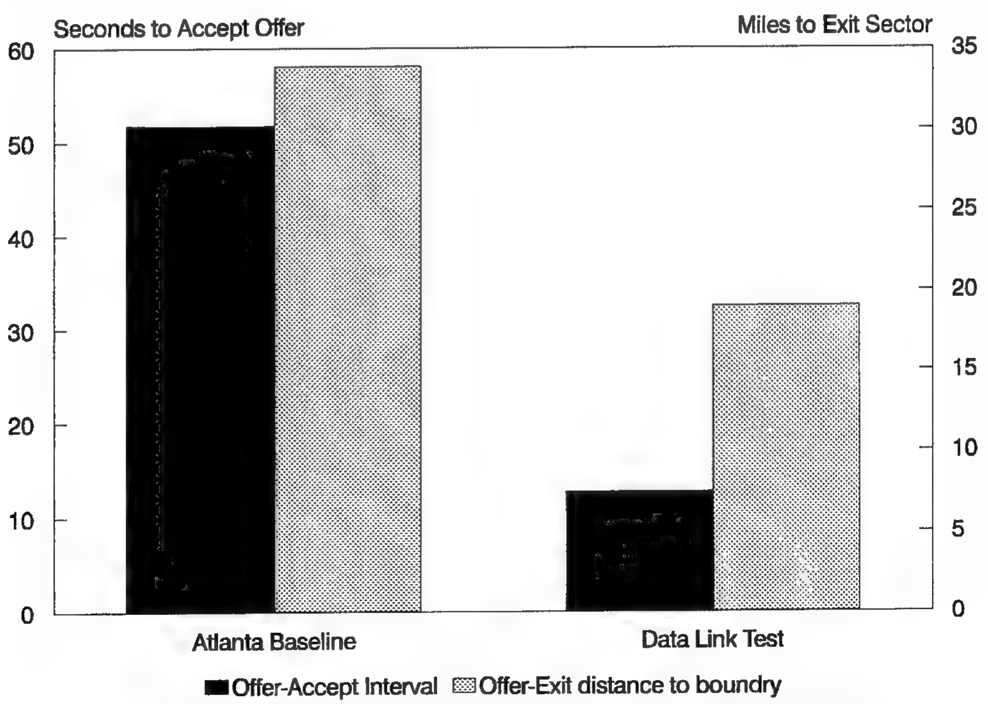

FIGURE 13. SECTOR 32 HANDOFF MEASURES

handoffs were accepted an average 38 seconds earlier during testing than they were on the baseline day.

The O-E Distance Flown is an index of the average distance from the aircraft boundary at which the sector 32 controllers offered a handoff to the next sector along the aircraft's route of flight. It was hypothesized that increased workload in sector 32 may have been evidenced either by offering handoffs earlier to shed load, or by an inappropriate delay in the handoff caused by overload attributable to other sector tasks.

The results show that, under Data Link testing, the controllers offered handoffs an average of 15 miles closer to the sector boundary than their counterparts did on the historical baseline day. The mean flight distance and time to the exit boundary were approximately 19 miles and 2.5 minutes, in comparison to 33 miles and 4.5 minutes for the baseline day. Both sets of values are within normal limits for offering handoffs.

Rather than being indicative of increased workload, the relatively reduced distance to the sector boundary under Data Link testing appears to have been the result of a strategy difference between normal voice and Data Link communications procedures. A typical strategy when using voice radio is to hand off an aircraft to the next sector well before reaching the boundary, but to retain communications capability until the controller is certain that no additional clearances must be sent to the aircraft.

The Data Link services provided the controllers with an option to select an automatic transfer of communication (TOC) feature. When set to the automatic mode, a TOC message was prepared and sent without further controller intervention when the manually entered handoff was accepted. This automatic feature was widely used by the teams in the present study.

In order to make effective use of the automatic TOC while retaining communications with the aircraft for the required period of time, the controllers adopted a strategy of delaying the handoff offer. As shown in the figure, this decreased the O-E Distance. However, as indicated by the supervisor ratings for handoff performance (section 5.1.4.2) and by the acceptable flight time and distance to the boundary that were achieved, the strategy had no discernible negative impact on ATC system performance.

5.1.5 Communications.

Measures of the nature and content of communications conducted on the baseline day and during testing were obtained as secondary outcome measures. As discussed in section 4.7.2.2, it was expected that any user benefit observed during testing would be associated with a redistribution of communications across the voice and Data Link media.

5.1.5.1 Voice Radio Usage.

Figure 14 illustrates the dramatic reduction in voice radio usage that occurred during testing when Data Link was available for ATC communications. As shown in the figure, during the rush period on the baseline day at the Atlanta ARTCC, the radio channel was occupied for more than 16.5 minutes. During Data Link testing, radio channel occupation time for the average sector 32 control team across all test runs dropped by 84 percent to less than 2.6 minutes.

Detailed analyses of the number and content of voice messages were

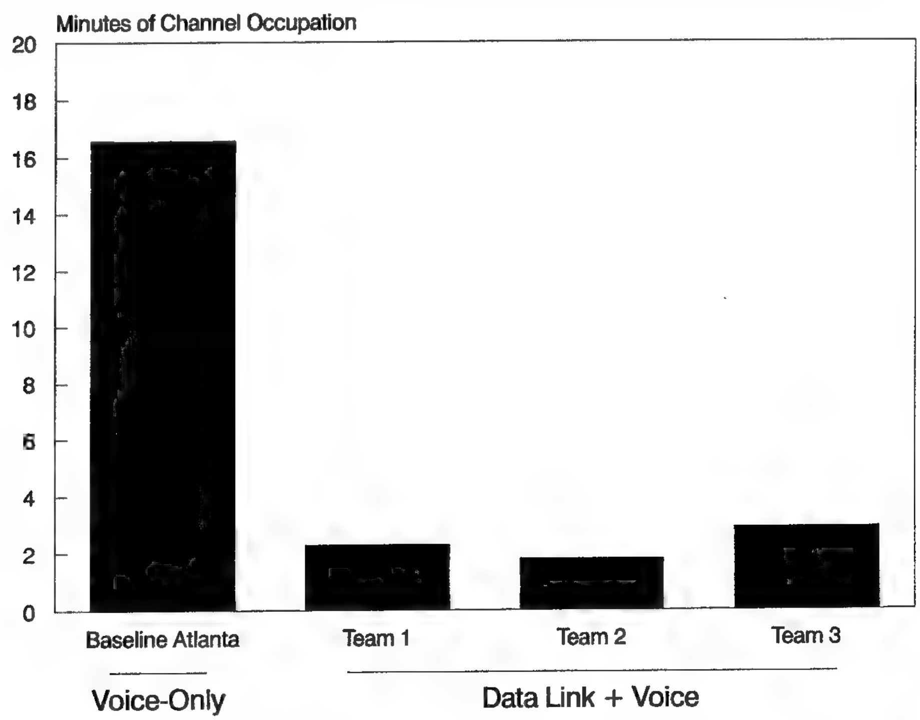

FIGURE 14. VOICE RADIO CHANNEL OCCUPATION TIME IN SECTOR 32

completed for the historical baseline rush period in sector 32 and the comparable 20 MIT Data Link tests. On the baseline day, the controllers made 217 voice transmissions while pilots made 179 transmissions. During Data Link testing at 20 MIT, the total number of controller voice transmissions dropped to an average of 23.3 while pilot transmissions fell to an average of 26. This equates to an average 88 percent reduction in combined pilot and controller voice messages.

Table 1 presents a breakdown of the types of voice messages sent by

TABLE 1. VOICE RADIO MESSAGES IN SECTOR 32 ON HISTORICAL BASELINE AND DATA LINK TEST DAYS AT THE 20 MIT RESTRICTION

Message Category	Baseline Atlanta	Data Link Team 1	Data Link Team 2	Data Link Team 3
Speed	7	0	0	0
Heading	7	1	2	3
Altitude	56	7	7	6
Combination Clearance	6	1	0	1
TOC	40	4	4	4
Route	9	0	3	5
Crossing Restriction	1	0	0	0
Initial Contact Response	13	2	1	1
Information	7	0	0	3
Request Information	19	5	1	1
Correction	10	1	1	1
Other Messages	22	2	1	2

controllers on the baseline day and during the corresponding Data Link test runs. As shown in the table, the availability of Data Link affected all types of controller voice messages, with major reductions accounted for by altitude clearances, transfer of communication messages, responses to initial contact calls, and "other" messages (primarily acknowledgments of messages received from pilots).

While they could not be replaced by the set of Data Link messages used in this experiment, it is interesting to note that voice radio corrections (repeats and clarifications) and requests for information from the pilots (e.g., "are you on frequency?", "say speed") were reduced during Data Link testing. This finding suggests that the persistent, visual controller and pilot displays associated with Data Link may have improved the effectiveness of ATC communications by reducing the need for redundant voice transmissions.

5.1.5.2 Data Link Usage.

The sector 32 control teams sent an average of 109 Data Link messages during each of the five test runs. All uplinks were either control clearances or TOC messages. No informational messages, corrections, or requests for information were sent using Data Link.

Table 2 presents a breakdown of the Data Link messages sent by each of the control teams during the 20 MIT test runs that were directly comparable to the historical baseline day under voice-only communications. As shown in the table, manually entered altitude messages, predefined clearances selected using the menu text function and TOC uplinks were the most frequently employed Data Link messages. For this study, the menus were customized by the individual teams prior to testing to include messages that they expected to send on a repetitive basis. In sector 32, the menus for all groups consisted of one or two altitude clearances, a number of route clearances to fixes, and crossing restrictions.

Table 2 also indicates that the three teams used Data Link to send all TOC messages to the 36 equipped aircraft. While teams 2 and 3 used the automatic TOC mode exclusively to send these messages, team 1 used the manual mode for approximately one-half of the aircraft.

Figure 15 summarizes the teams' use of Data Link across the five test conditions. The histograms present the number of messages averaged

TABLE 2. DATA LINK MESSAGES IN SECTOR 32 ON THE DATA LINK TEST DAYS AT THE 20 MIT RESTRICTION

Message Category	Data Link Team 1	Data Link Team 2	Data Link Team 3
Speed	11	9	8
Heading	11	0	1
Altitude	57	22	16
Combination Clearance	0	0	1
Menu Text (1)	22	34	43
Free Text (2)	2	1	2
TOC Auto	16	36	36
TOC Manual	20	0	0

(1) All items selected from menu - includes additional altitude clearances, route clearances direct to a fix and crossing restrictions.

(2) Text messages composed on-line - includes additional headings, special route clearances, and a clearance to an altitude at a prescribed climb rate.

across the three teams and divided into TOC and clearance transmissions. While some variation in the total number of Data Link messages is evident in the graph, no consistent relationship is apparent between the difficulty/complexity of the control problem and the use of the Data Link system. Thus, the control teams did not abandon Data Link in favor of the traditional voice channel when traffic density increased or when the number of aircraft were raised by 10 percent.

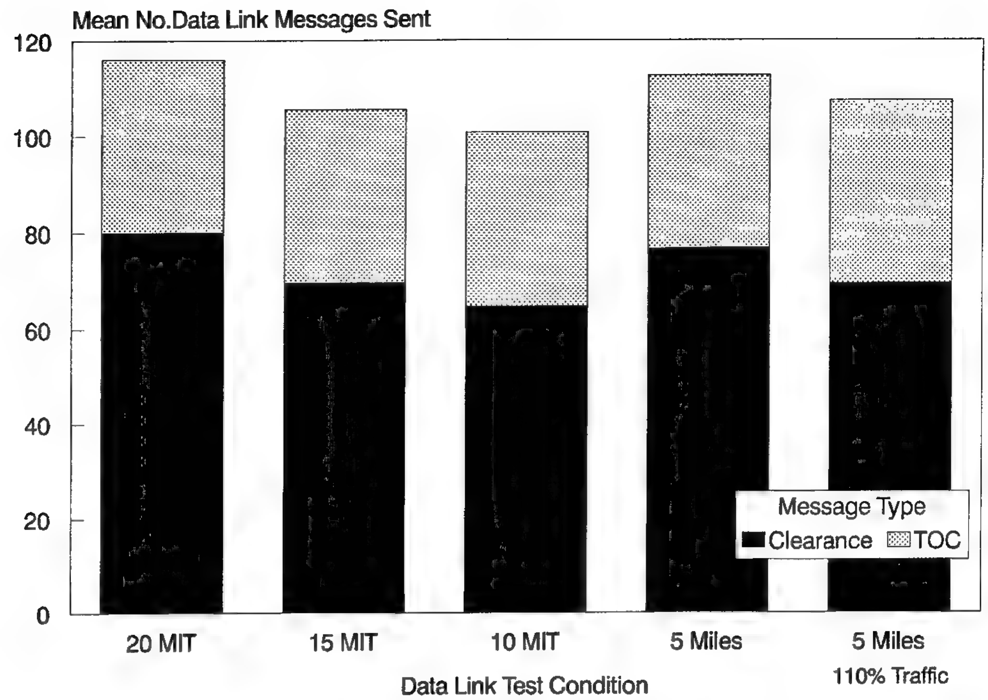

FIGURE 15. DATA LINK MESSAGES SENT IN SECTOR 32

5.2 EXPERIMENT 2 -- ARRIVAL SECTOR.

As described in section 4, the hypothesized user benefit of Data Link communications for experiment 2 was an improvement in the efficiency with which aircraft would be controlled in sector 09 and delivered to the arrival fix for the Atlanta airport. The following subsections first present data on the criterion safety measures that were collected on each of the five test runs completed by the three teams of sector 09 controllers. Sector throughput and efficiency data are then presented for the test runs that were safely accomplished by the subjects.

5.2.1 Criterion Performance.

5.2.1.1 Aircraft Separation.

Aircraft separation was continuously monitored at the Host operator's console during each test run. No operational errors (minimum en route separation violations) were recorded between aircraft in sector 09 on any of the five test runs for any of the three teams of controllers.

5.2.1.2 Operational Safety Assessments.

Controller and Supervisor Ratings

Expert operational assessments of the safety with which the test runs were completed are shown in figure 16. The histogram presents the frequency

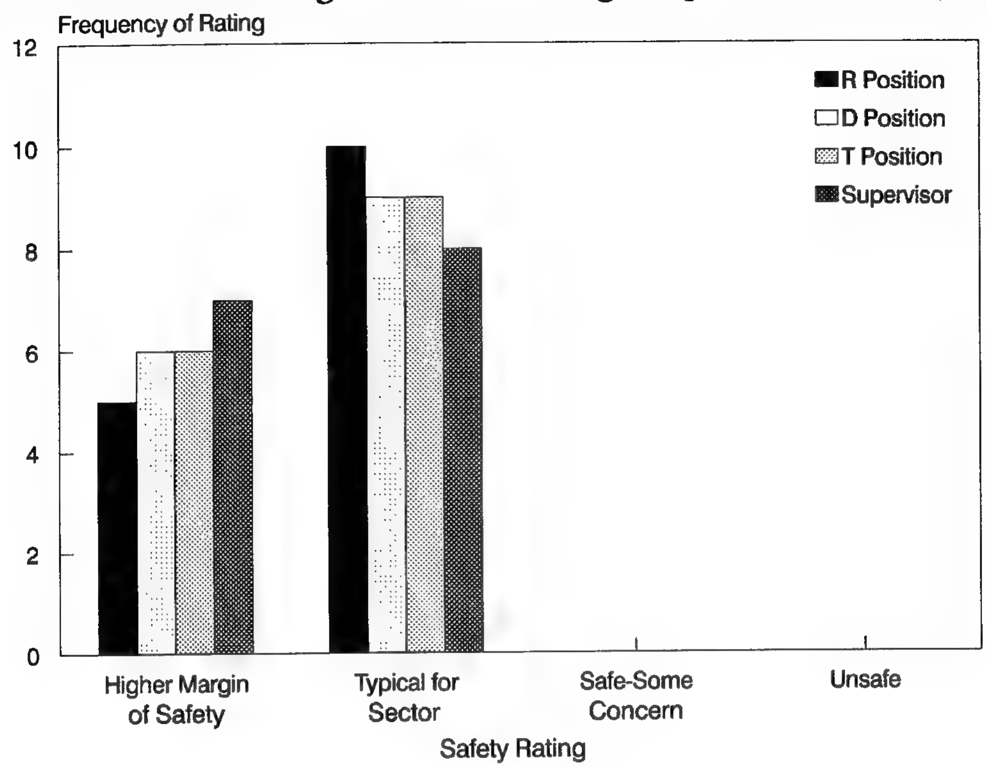

FIGURE 16. SECTOR 09 SAFETY RATINGS

with which the 15 test runs (5 per team) received each of the 4 possible safety ratings from the radar, data and tracker controllers as well as the observing supervisor for the sector.

None of the controllers or supervisors rated any of the test runs as "unsafe." As in experiment 1, the supervisors assigned the test runs the highest safety ratings overall with seven runs rated as having a greater margin of safety than normal for the sector in the operational, voice-only environment, and eight runs rated as having typical levels of safety. The controllers rated the margin of safety of approximately one-half of the runs as typical for the sector (24 of 45 ratings), with the remaining runs rated as having a higher margin of safety than normal. No ratings of "safe, but some concern" were received.

Examination of the ratings across the test runs revealed no evidence for a reduction in perceived safety with changes in the number of aircraft under control. On the 1 (higher margin of safety) to 4 (unsafe) scale, average team ratings for the three groups of controllers and their supervisors were consistently at or below 1.67 from the first run with baseline traffic levels to the last run in which the number of aircraft arriving at Atlanta was increased by 40 percent.

Pilot Ratings

Pilot safety assessments were performed as part of a post run questionnaire completed by the two pilots who flew each full fidelity flight simulator during the test runs, and by simulation site coordinators who acted as observers. They rated the flights on a scale ranging from "completely safe" (1) to "completely unsafe" (7).

The FAA RCS (B747), NLR B747, Avia 727, and FAA GAT simulators participated in all sector 09 flights, while the OKC B727 participated in only the final two replications of the study. All five simulators were equipped to receive Data Link messages. On each test run, the Avia and RCS completed one test flight, while the remaining simulators completed two test flights. This yielded a total of 110 safety rating opportunities over the entire experiment.

For the purpose of analysis, the three ratings for each flight were summed to produce a scale with a minimum value of 3 (completely safe) to 21 (completely unsafe). Of the 110 flights, 75 (68 percent) received combined ratings of 3, indicating unanimous agreement among the raters that the flight had been completely safe. Of the remaining 35 flights, 33 combined ratings were below the combined scale midpoint of "12", with 22 of these rated as "5" or lower.

Two of the 110 flights received combined scores higher than the scale midpoint. Both of these were produced in flights completed by the same simulator. In one case the observer, PF and PNF assigned the flight individual ratings of 5, 5, and 7, respectively on the 1 to 7 scale. Written comments from the three raters indicated that the poor safety judgments were caused by a flaw in the operation of the Data Link pilot interface used in the simulator. The pilots were unable to use the recall feature of the equipment to review an earlier ATC message because the displayed pointer was not correctly aligned with the appropriate actuation button on the display bezel.

In the second case, the observer, PF and PNF assigned the flight ratings of 6, 7, and 7, respectively. Comments from these raters implicated a software failure in the simulation equipment or noise in the long distance data transmission system. At one point during the flight, the pilots reported a rapid influx of Data Link messages presented on the "message pending" display. No corresponding uplinks had been sent by the test controllers. When called to the display, the "messages" were found to be data error messages. Each of these disrupted the Data Link connection and prevented further communication during the test flight.

The incidents described above indicate that the two poor safety ratings were attributable to local problems in a single simulator. Since neither rating was caused by controller error or by inherent problems with Data Link ATC communications, the associated test runs were not judged invalid.

5.2.2 Sector Throughput.

The findings presented in section 5.2.1 indicate that the control teams in all three replications of the study were able to safely control the baseline aircraft sample in sector 09, as well as the increases in Atlanta arrival traffic ranging from 10 to 40 percent. The following three subsections present data on changes in sector throughput and aircraft operating efficiency associated with the use of Data Link to supplement the ATC communications channel in this sector.

5.2.2.1 Baseline Traffic.

The central question that was addressed in this experiment was whether sector 09 control teams using a combined voice and Data Link communications system could improve the efficiency with which Atlanta arrival traffic typically is controlled during the target rush period. Figure 17 presents the mean time and distance flown by Atlanta arrival aircraft on the historical baseline day and on the three Data Link test runs which duplicated the baseline day traffic.

As shown in the figure, the addition of Data Link communications was associated with a reduction in mean Atlanta arrival aircraft flight time and distance in sector 09. The average arrival aircraft on the historical baseline day flew 111 miles in the sector over more than 18 minutes. In contrast, when under control of the Data Link teams, the average aircraft flew less than 89 miles over approximately 14 minutes.

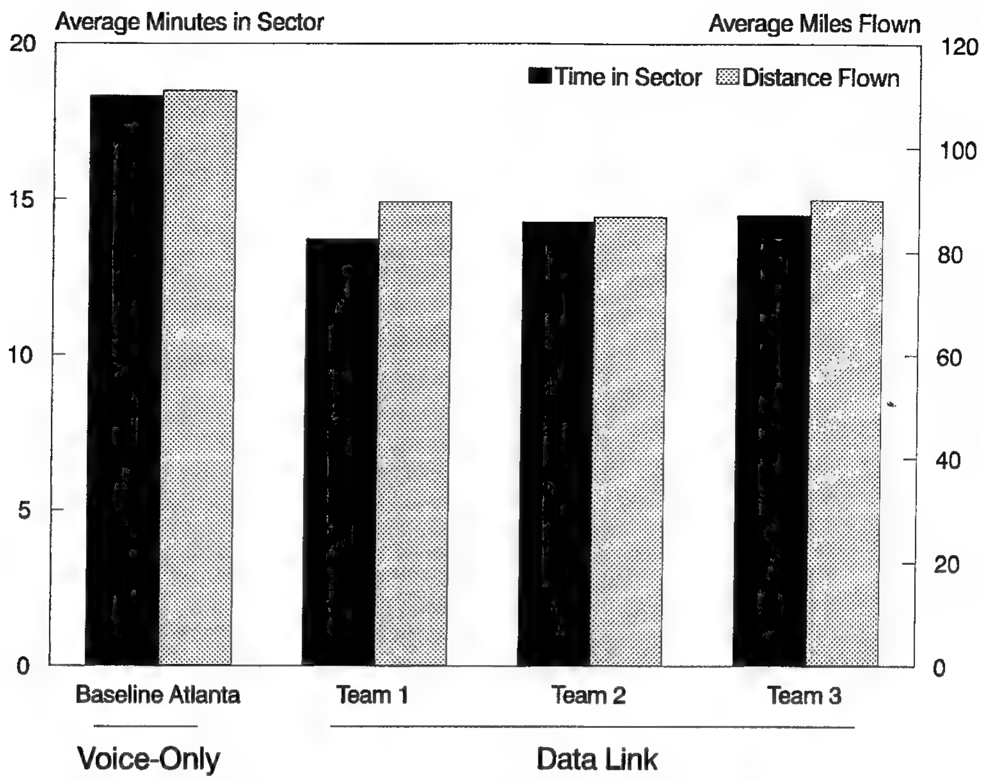

FIGURE 17. AVERAGE AIRCRAFT TIME AND DISTANCE FLOWN IN SECTOR 09

As in experiment 1, traditional statistical significance testing of these findings was not possible because of the small number of control teams that could be tested. However, the practical significance of the findings can be inferred from figure 17 by noting the consistent improvement in sector throughput displayed by the three independent test teams in comparison to the voice-only control team on the representative historical sample day.

An alternative statistical analysis comparable to that performed on the data from experiment 1 was conducted by treating the individual Atlanta arrival aircraft as subjects, and comparing each aircraft's flight efficiency on the baseline day to its performance under the three test teams' control on the simulation run with identical traffic demands. The repeated measures analysis of variance verified that arrival efficiency with Data Link was significantly better than that on the baseline day with voice-only communications ($F_{13,42}=5.80$, $p<.01$).

In agreement with the results for experiment 1, figure 17 also shows that the flight time and distance measures were closely associated, indicating that the controllers did not use potentially inefficient speed increases to decrease time in sector. Evaluation of the aircraft track profiles suggests that other control techniques were employed during Data Link testing to increase flight efficiency.

Figure 18 presents the horizontal track plots for a sample of 15 Delta Airlines aircraft that flew during the historical rush period and during Data Link test scenarios which duplicated the baseline traffic pattern. Each of the plots shows the aircraft sample entering sector 09 and proceeding into the sequence to cross the Tiroe arrival fix at the specified altitude restriction. On the historical baseline day, it can be seen that the sequence was merged at a greater distance from Tiroe than on the Data Link test trials. Sequencing at the merging point on the baseline day was accomplished in a tactical fashion, with most aircraft vectored into a holding pattern to attain their positions in the arrival sequence.

In contrast, the controllers using the combined voice and Data Link communications system were able to provide more strategic ATC service which resulted in much more efficient aircraft operation. While some vectoring to achieve sequencing is apparent, none of the aircraft were required to enter holding patterns. In addition, many of the aircraft appear to have been cleared directly to Tiroe, providing them with "short cut" routes to the arrival fix.

Figure 19 separates the flight time and distance data for the three categories of air traffic that flew in sector 09 on the historical baseline day and during Data Link testing with the identical traffic pattern. As shown in the figure, the 23 Atlanta arrivals reflect the improvement in flight efficiency that was discussed above. The other traffic in the scenario were 4 aircraft bound for the satellite Peachtree Dekalb airport (PDK), and 14 overflights. The testing results show no appreciable change from the baseline day in flight time or distance for the PDK arrivals, and an apparent increase in efficiency for the overflights. This finding confirms that the improvements for aircraft in the primary Atlanta arrival traffic flow were not attained by sacrificing ATC service to other aircraft.

5.2.2.2 Increased Traffic.

The final four simulation runs completed under Data Link testing were used to assess the control teams' ability to deal with increases in the

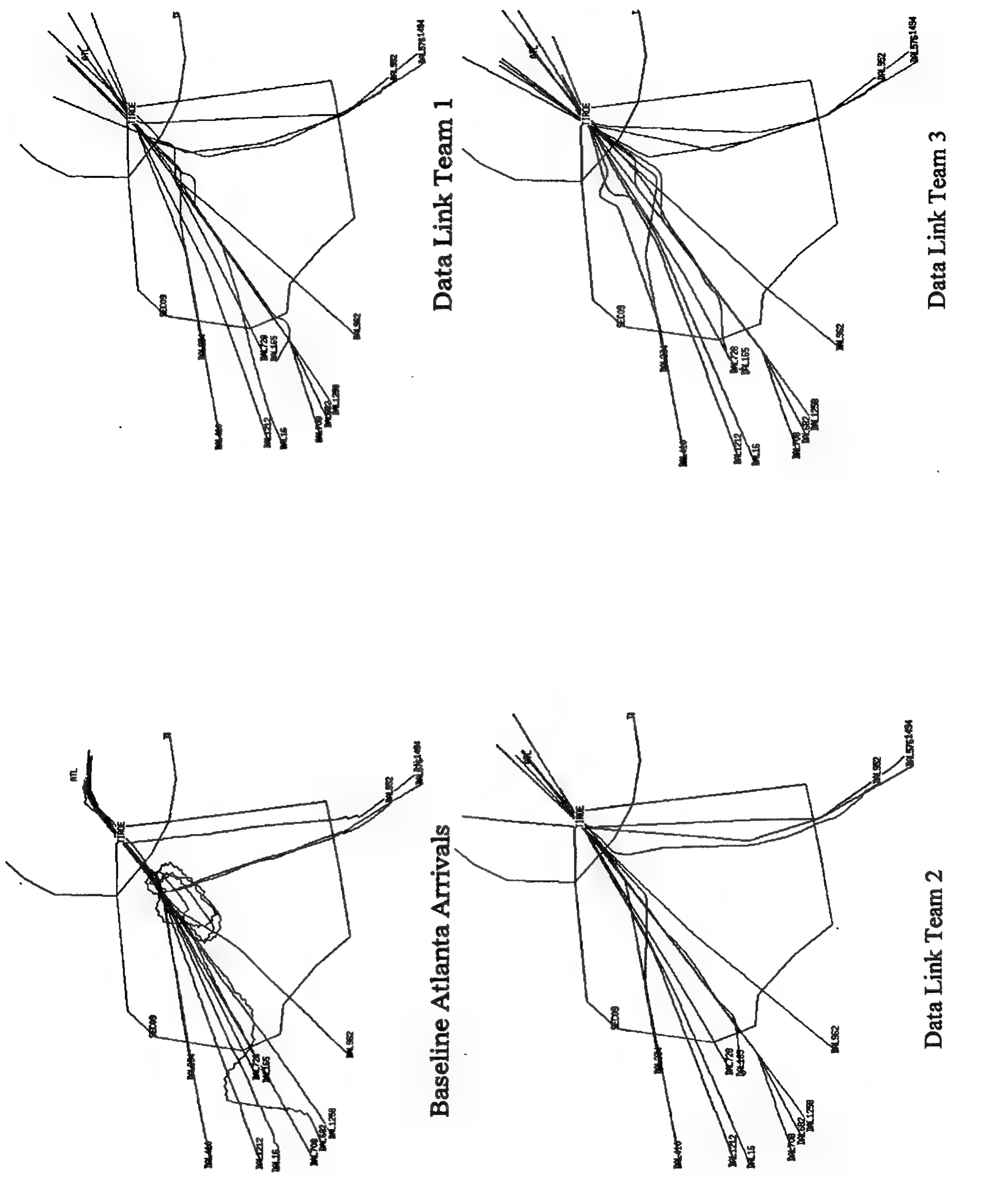

FIGURE 18. SAMPLE SECTOR 09 ATLANTA ARRIVAL TRACK PLOTS

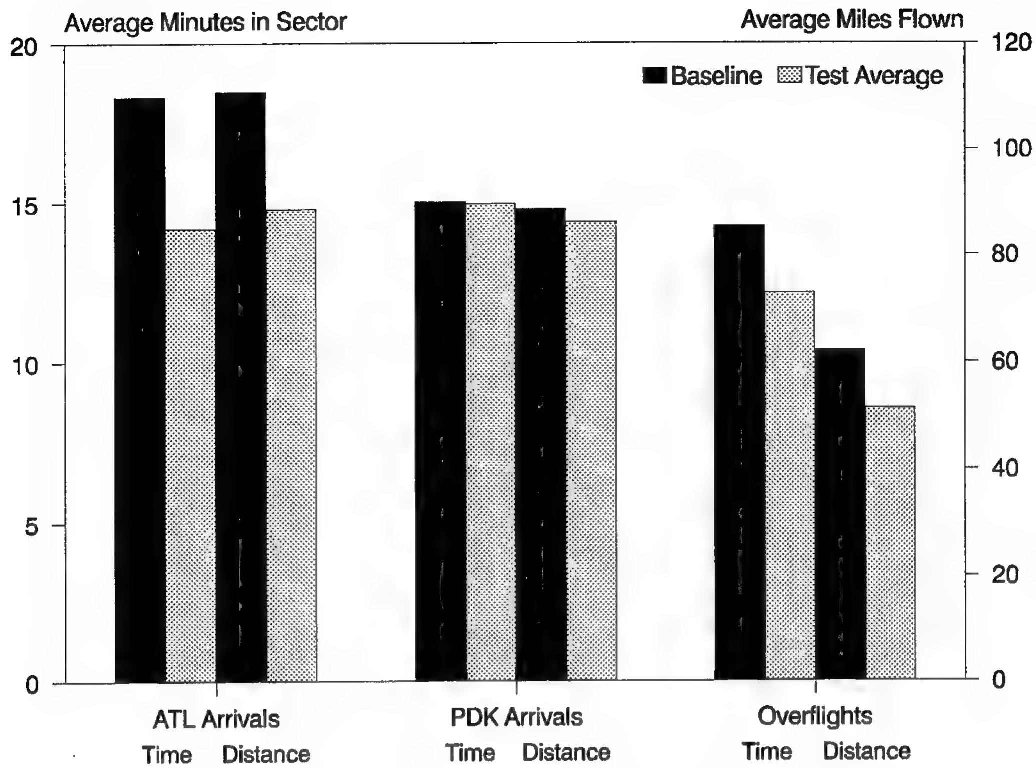

FIGURE 19. TIME AND DISTANCE FLOWN IN SECTOR FOR ATLANTA ARRIVALS, PDK ARRIVALS, AND OVERFLIGHTS

Atlanta arrival traffic sample. A fast-time SIMMOD model was used to provide comparative baseline data for flight efficiency data collected during these runs.

The detailed SIMMOD model of the sector 09 traffic flow was developed by analyzing traffic routing, resulting aircraft interactions, and travel times from the historical baseline sample day rush period. The model parameters were adjusted to duplicate the actual traffic flow by imposing the varied MIT restrictions for aircraft at the Tiroe fix that were used on the sample day, and by eliminating interactions between the jet and turboprop aircraft that flew at different altitudes. The adjusted model produced a close match to the actual baseline data derived from the historical SAR tape. The model calculations yielded an average time in sector estimate of 18.12 minutes in comparison to 18.32 minutes for the actual baseline day.

Baseline data for comparison to the Data Link test results were generated by challenging the capabilities of the voice communications-based SIMMOD sector model with increased traffic levels. The timing and sector entry points of the flights that were added to the input file to the model were identical to those added to the scenarios for the 110, 120, 130, and 140 percent test runs.

Figure 20 compares the modeled baseline data to that obtained under testing with Data Link. Increasing the number of arrival aircraft from 25 to 31 produced an expected average increase in the total aircraft time in sector both in the voice communications-based model and during Data Link testing. As shown in the figure, however, the overall reduction in average aircraft sector time demonstrated during Data Link testing with the baseline number of aircraft was maintained as traffic levels increased. In comparison to the voice communications-based model estimates, Data Link saved from 3 to 4 minutes in sector flight time for the average aircraft when traffic levels rose by 10 to 40 percent.

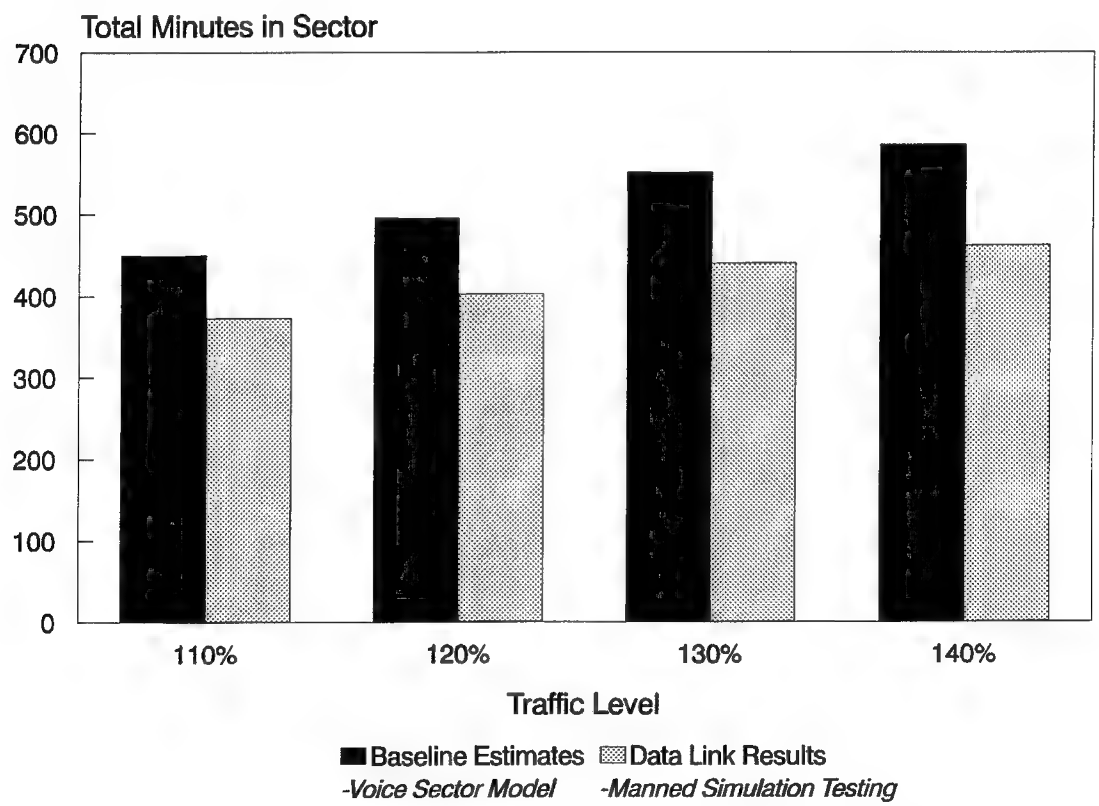

FIGURE 20. AVERAGE TIME IN SECTOR 09 FOR INCREASED TRAFFIC

In addition, examination of average sector flight times indicates that the disparity between Data Link and voice-only communications may increase as traffic demand is raised. While the average reduction in sector flight time with Data Link was 3.07 minutes at the 110 percent level of traffic, the savings increased to 3.4 minutes at 120 percent, 3.83 minutes at 130 percent, and 3.96 minutes at 140 percent. Thus, it appears that the overall increase in the capacity of the communications channel with Data Link may reduce the rate of growth in average aircraft flight time as the system is challenged by increasing traffic demands.

Figure 21 shows the processing time for all Atlanta arrival aircraft averaged across teams for each test condition. Processing time was calculated for the baseline day and the test conditions by subtracting the problem exit time for the first Atlanta arrival aircraft leaving sector 09 from that of the last aircraft. The problem exit time for each aircraft was defined as the time of day at which the aircraft crossed the Tiroe arrival fix. Thus, processing time reflects the time needed to complete the sector's task of merging the traffic sample during the rush period in order to place the aircraft on their common arrival route into the low altitude terminal area.

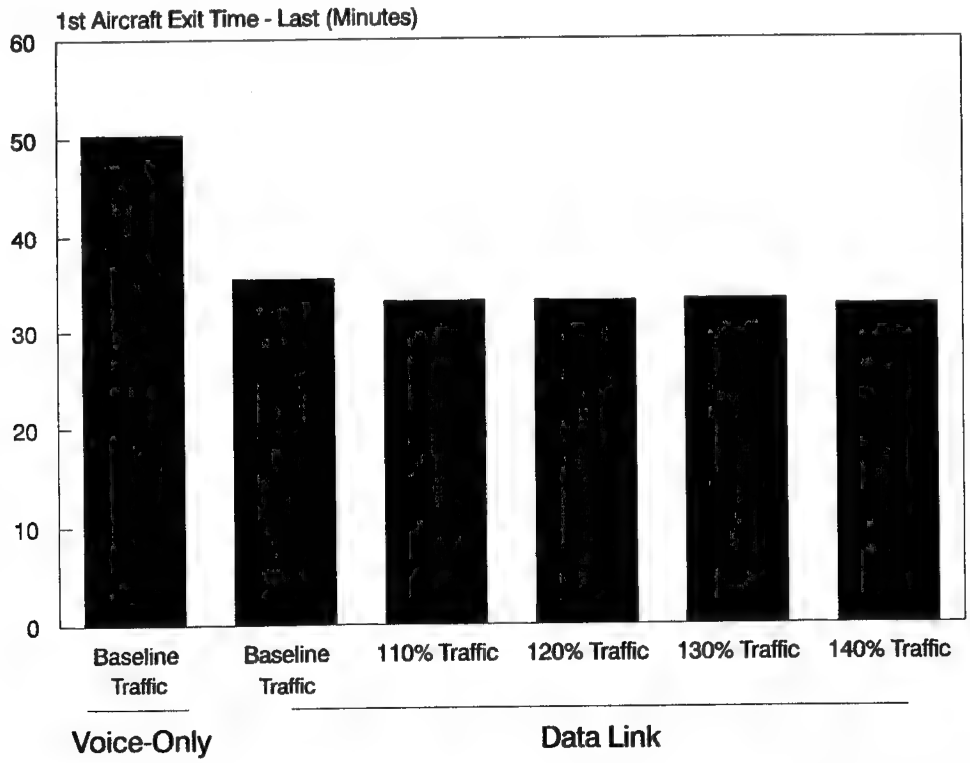

FIGURE 21. ARRIVAL TRAFFIC PROCESSING TIME IN SECTOR 09

This view of the data demonstrates that the reduced flight times and distances discussed above were effectively realized in an overall improvement in the productivity of the sector. As shown in the figure, over 50 minutes were needed to process all of the arrivals on the historical baseline day. Under testing where the communications channel was expanded by Data Link, processing time was reduced by an average of 14.8 minutes (29 percent) for the identical traffic sample. The data also show that Atlanta arrival processing time was reduced even when the arrival traffic sample was increased by up to eight aircraft.

Section 6 presents estimates of the economic benefits associated with the in-flight efficiency improvements demonstrated in this experiment.

5.2.3 Sample Fuel Consumption.

As discussed in section 4.7, this experiment focused on measurements of flight time and distance to assess aircraft operating efficiency. However, fuel consumption data were recorded for piloted aircraft simulators in order to provide representative examples of the way in which these savings would be reflected in reduced usage of resources. Estimates of fuel consumption were calculated by models associated with four of the simulators that participated as Atlanta arrival flights. All comparisons were made between the historical baseline flights and the initial test runs with Data Link in which the traffic sample duplicated that on the baseline day.

Table 3 presents the average reduction in flight time and corresponding fuel savings for four flights completed by the simulators during testing. All four of these flights had received extensive vectoring or had been directed to a holding pattern on the historical sample day. In all cases under Data Link testing, these flights achieved an earlier arrival at the Tiroe fix and consumed less fuel.

5.2.4 Secondary Criterion Measures.

The primary operational safety measures described in section 4 were used as criteria for validating the NAS user benefits identified during testing. As in experiment 1, a secondary group of measures was used in this experiment to determine whether the user benefits were achieved at any expense to the general quality of task performance exhibited by the controllers or any significant increase in the workload levels that they experienced.

TABLE 3. SAMPLE AVERAGE FLIGHT TIME AND FUEL SAVINGS FOR SELECTED SECTOR 09 FLIGHTS FLOWN BY FLIGHT SIMULATORS

Atlanta Arrival Flight (Simulator)	Flight Time Savings (minutes)	Fuel Savings (pounds)
DAL 772 (NLR B747)	18.18	3827
DAL 16 (RCS B747)	10.07	1811
DAL 952 (Avia B727)	10.29	884
DAL 165 (OKC B727)	14.09	572

5.2.4.1 Supervisor Performance Ratings.

During each test run, the sector 09 supervisors judged the control team on nine factors indicative of degraded sector performance. A 5-point rating scale ranging from 1 “never occurred” to 5 “occurred unacceptably often” was used to quantify the judgments.

Ratings on each dimension for the five test conditions averaged across the three supervisors are summarized in figure 22. None of the average ratings exceeded the midpoint on the scale (3 - “within normal limits for the sector during this duty period”). Inspection of the data for individual teams indicated that all of the five ratings of the nine factors made by each supervisor were “within normal limits” or better. As shown in figure 22, the mean ratings also did not reveal any tendency for deterioration in sector performance as the traffic demands were increased across the test runs.

5.2.4.2 Controller Workload.

Controller workload was assessed using a subjective rating scale of perceived effort. Following each test run, the controllers rated their workload on a 5-point scale in comparison to their normal workload at sector 09 for the same work period. Figure 23 presents the mean workload ratings for each control position across the five test runs.

As indicated by figure 23, the mean ratings suggest that there was no apparent trend for average workload ratings to increase when the traffic demand was raised over the five test runs. However, the data do reveal a consistent difference in relative workload across the three control

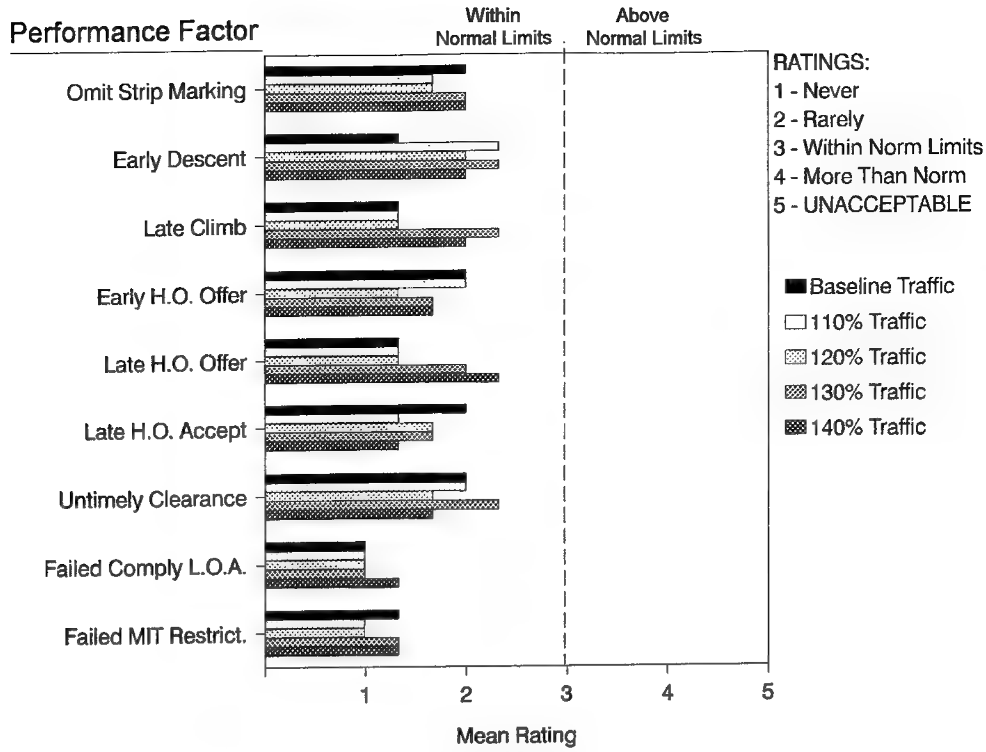

FIGURE 22. SECTOR 09 SUPERVISOR RATINGS OF CONTROLLER PERFORMANCE

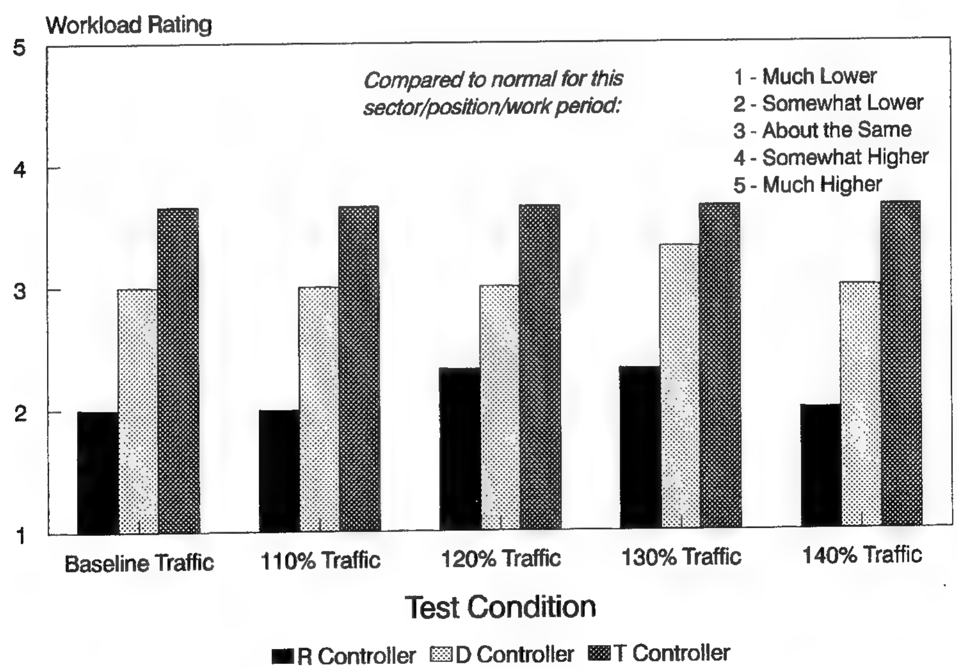

FIGURE 23. SECTOR 09 CONTROLLER WORKLOAD RATINGS

positions. Regardless of the test condition, all three controllers at the radar position indicated that their workload was either "about the same" or lower than that for their position at the operational sector 09 during the same rush period. In contrast, the ratings received from the controllers at the data and tracker positions sometimes suggested that workload was either "somewhat" or "much higher."

Specifically, the tracker controllers on two teams consistently rated their workload as somewhat higher, while the third indicated that it was about the same. Likewise, the data controller on one of the teams indicated that his workload was "much higher than normal," while the remaining two consistently rated their workload as about the same or somewhat lower.

Rather than indicating a potential workload problem during testing, these ratings are likely to be indicative of the redistribution of sector tasking that occurred when the combined Data Link and voice radio communications capability was introduced. As discussed in a later section of these results, the control teams in both experiments adopted procedures under which the radar controller performed all voice radio communications and directed the tracker and data controllers to send and monitor Data Link transactions (see section 5.3.1). Among other effects, this freed the radar controller to coordinate and share control decision making with his associates. Such team activity contrasted sharply with a typical busy sector under voice-only communications where the radar position can be completely occupied with communications and the associates' assistance is necessarily confined to peripheral duties.

This explanation of the somewhat disparate workload ratings was supported by written comments solicited after each test run. The controller who had rated all runs as having much higher workload than normal at sector 09 during the same work period indicated that his workload at the data position was higher because he was able to help much more than he normally could. Rather than being detrimental, the workload increase was associated with increased productivity.

Similar comments were obtained from controllers who staffed the tracker position to explain their relative workload ratings. None of the ratings obtained from any of the teams were accompanied by comments suggesting that increases in controller workload had posed any risk of poorer performance.

5.2.4.3 Handoff Measures.

Measures of controller performance in accepting handoffs from, and offering handoffs to, adjacent sectors were collected during the experiment as subsidiary workload indices. Figure 24 presents results for two handoff measures obtained from the baseline Atlanta SAR tape and the comparable baseline traffic test run with Data Link. As discussed below, neither measure indicated that controller workload under Data Link testing had affected sector handoff performance.

The O-A Interval is an index of the average time taken by the control team to accept an aircraft handoff from a sending sector. As discussed in experiment 1, the use of this measure was based on the hypothesis that unacceptable increases in workload may have been reflected by delays in accepting the handoff offer. No evidence of controller overload during Data Link testing was provided by this measure. In fact, as shown in figure 24, handoffs were accepted an average 35 seconds earlier during testing than they were on the baseline day.

The O-E Distance Flown is an index of the average distance from the

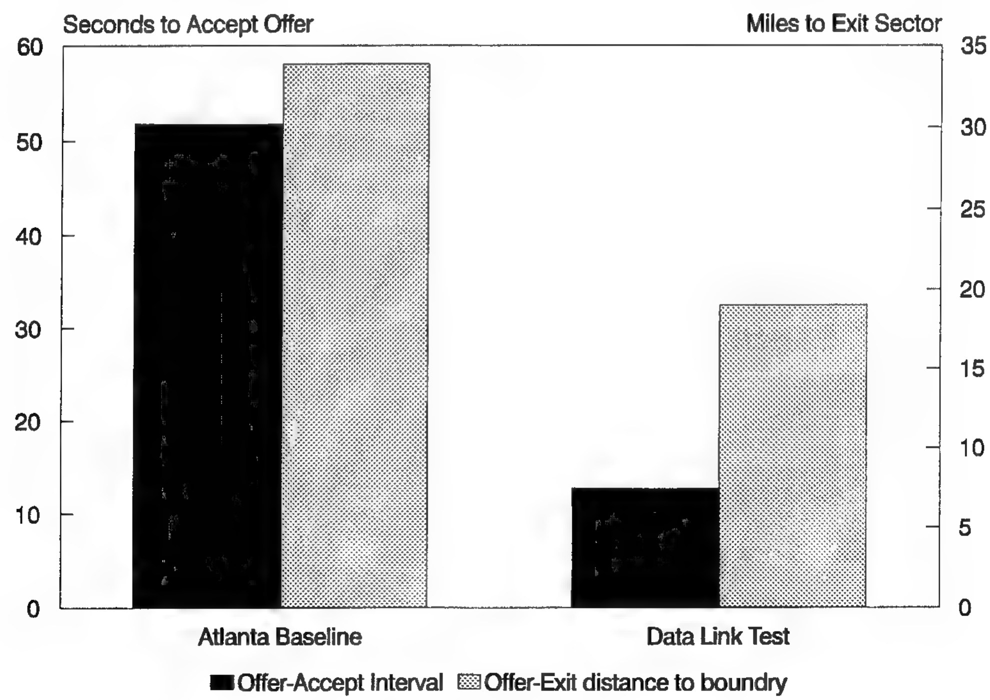

FIGURE 24. SECTOR 09 HANDOFF MEASURES

boundary at which the sector 09 controllers offered a handoff to the next sector along the aircraft's route of flight. It was hypothesized that excessive workload in sector 09 may have been evidenced either by offering handoffs earlier to shed load, or by an inappropriate delay in the handoff caused by overload attributable to other sector tasks.
The results show that, under Data Link testing, the controllers offered handoffs an average of 5.1 miles closer to the sector boundary than their counterparts did on the historical baseline day. The mean flight distance and time to the exit boundary were approximately 25.4 miles and 5.1 minutes, in comparison to 30.5 miles and 5.8 minutes for the baseline day. Both sets of values are within normal limits for offering handoffs.

As in sector 32, the relatively reduced flight distance to the sector boundary following a handoff offer that was observed during sector 09 Data Link testing appears to have been the result of a strategy difference between normal voice and Data Link communications procedures rather than load shedding. In order to make effective use of the automatic Data Link TOC while retaining communications with the aircraft for the required period of time, the controllers adopted a strategy of delaying the handoff offer. As shown in the figure, this decreased the O-E Distance. However, as indicated by the "within normal limits" supervisor ratings for handoff performance (section 5.2.4.1) and by the acceptable flight time and distance to the boundary that were achieved, the strategy had no discernible negative impact on ATC system performance.

5.2.5 Communications.

Measures of the nature and content of communications conducted on the baseline day and during testing were obtained as secondary outcome measures. As discussed in section 4.7.2.2, it was expected that any user benefit observed during testing would be associated with a redistribution of communications between the voice and Data Link media.

5.2.5.1 Voice Radio Usage.

Figure 25 illustrates the reduction in voice radio usage that occurred during testing when Data Link was available for ATC communications. As shown in the figure, during the rush period on the baseline day at the Atlanta ARTCC, the radio channel was occupied for more than 16 minutes. During Data Link testing, radio channel occupation time for the average sector 09 control team during all five test runs dropped by 78 percent to 3.5 minutes.

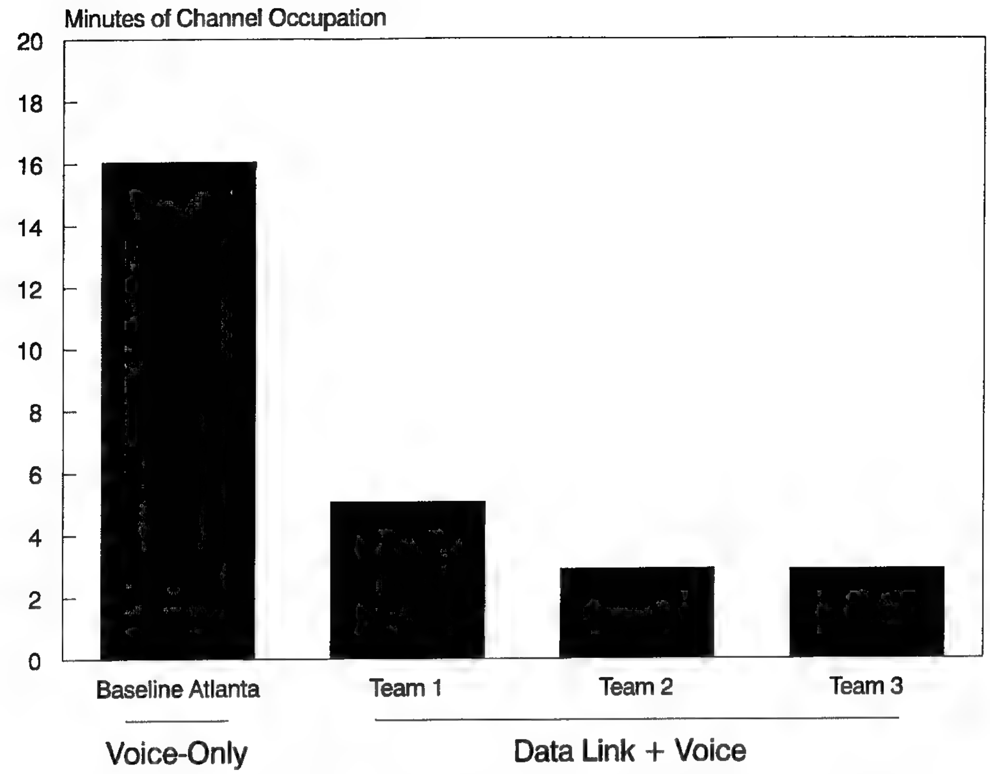

FIGURE 25. VOICE RADIO CHANNEL OCCUPATION TIME IN SECTOR 09

Detailed analyses of the number and content of voice messages were completed for the historical baseline rush period in sector 09 and the comparable baseline traffic Data Link tests. On the baseline day, the controllers made 159 voice transmissions while pilots made 183 transmissions. During Data Link testing, the total number of controller voice transmissions dropped to an average of 48.7 while pilot transmissions fell to an average of 44.7. This equates to a 73 percent reduction in combined pilot and controller voice messages.

Table 4 presents a breakdown of the types of voice messages sent by controllers on the baseline day and during the corresponding Data Link test runs. As shown in the table, the availability of Data Link affected almost all types of controller voice messages, with major reductions accounted for by altitude clearances, crossing restrictions, transfer of communication messages, and responses to initial contact calls.

TABLE 4. VOICE RADIO MESSAGES IN SECTOR 09 ON HISTORICAL BASELINE AND DATA LINK TEST DAYS WITH BASELINE TRAFFIC

Message Category	Baseline Atlanta	Data Link Team 1	Data Link Team 2	Data Link Team 3
Speed	5	7	3	0
Heading	4	12	7	7
Altitude	31	17	6	2
Combination Clearance	5	0	2	1
TOC	34	3	3	3
Route	10	1	3	6
Crossing Restriction	25	3	2	5
Initial Contact Response	22	2	2	2
Information	9	0	0	0
Request Information	1	13	2	5
Correction	11	4	1	4
Other Messages	9	10	3	5

5.2.5.2 Data Link Usage.

The sector 09 control teams sent an average of 143 Data Link messages during each of the five test runs. All uplinks were either control clearances or TOC messages. No informational messages, corrections, or requests for information were sent using Data Link.

Table 5 presents a breakdown of the Data Link messages sent by each of the control teams during the test run that was directly comparable to the historical baseline day under voice-only communications. As shown in the table, manually entered altitude messages, predefined clearances selected using the menu text function and TOC uplinks were the most frequently employed Data Link messages.

For both experiments of this study, the menus were customized by the individual teams prior to testing to include messages that they expected to send on a repetitive basis. In sector 09, the menus for all groups consisted of two speed controls and a number of route clearances to fixes, most with

TABLE 5. DATA LINK MESSAGES IN SECTOR 09 ON THE DATA LINK TEST DAYS WITH BASELINE TRAFFIC

Message Category	Data Link Team 1	Data Link Team 2	Data Link Team 3
Speed	15	14	5
Heading	7	6	4
Altitude	32	41	17
Combination Clearance	0	0	2
Menu Text (1)	28	29	32
Free Text (2)	6	1	0
TOC Auto	31	31	31
TOC Manual	0	0	0

(1) All items selected from menu - includes additional altitude clearances, route clearances direct to a fix and crossing restrictions.

(2) Text messages composed on-line - includes additional headings, special route clearances, and a clearance to an altitude at a prescribed climb rate.

crossing restrictions. Table 5 also indicates that the three teams used Data Link to send all TOC messages to the 31 equipped aircraft. The automatic TOC mode was used exclusively to send these messages.

Figure 26 summarizes the teams' use of Data Link across the five test conditions. The histograms present the number of messages divided into TOC and clearance transmissions and averaged across the three teams. As shown in the figure, the mean number of Data Link transmissions increased in a linear fashion with increases in the size of the traffic sample in sector 09. Thus, the control teams did not abandon Data Link in favor of the traditional voice channel as the complexity of the ATC scenario was raised during testing.

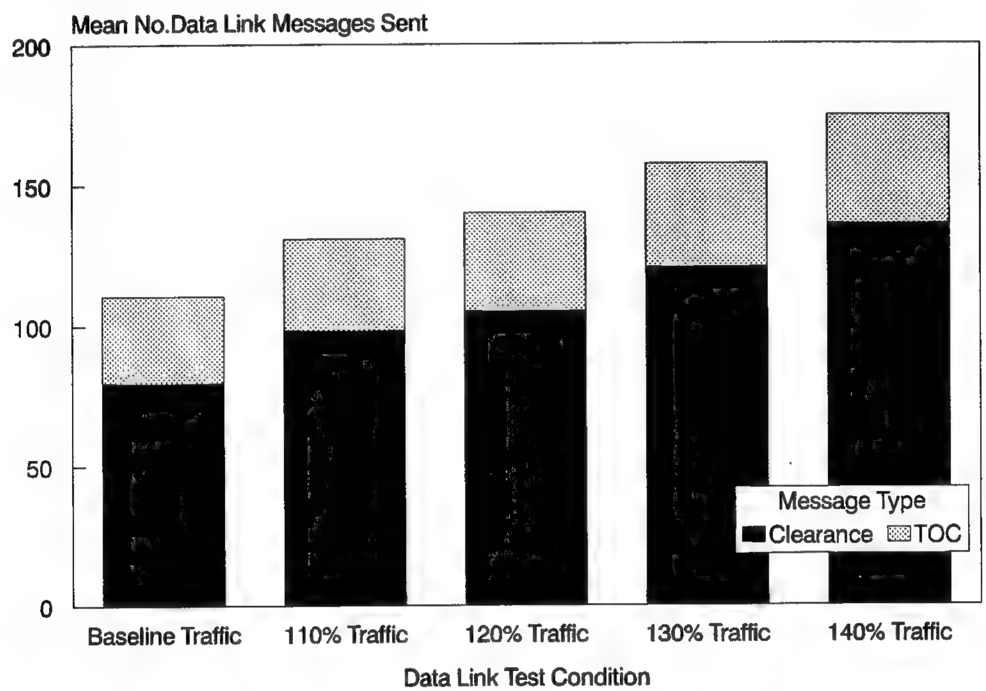

FIGURE 26. DATA LINK MESSAGES IN SECTOR 09

5.3 SUBSIDIARY MEASURES.

The primary goal of this study was to identify and measure some of the user benefits associated with two-way Data Link ATC services. However, because of the unique research opportunity provided by the large-scale, high fidelity simulation environment, additional data were collected during both experiments to examine a group of human factors and technical issues associated with Data Link ATC communications.

5.3.1 Control Team Duty Profiles.

As noted earlier in this report, teams of three controllers were used in both experiments to duplicate sector staffing during the historical baseline day rush periods. Since this study was the first in which Data Link communications were tested at a sector manned by control teams rather than single radar controllers, data were collected to identify the procedures adopted by the teams to accomplish communications and other ATC tasks.

The duty profiles completed by the controllers following each test run provided information on how the control teams allocated tasks among the three members. Correlational analysis of the data was used to determine whether the duty profiles provided by the subjects varied across the five test runs. The Kendall's Coefficient of Concordance (W) computed for all positions on each sector were consistently greater than .90, indicating that each team maintained its profile for division of duties as testing progressed.

In addition, the data indicate that the three teams of controllers who participated at each sector adopted similar duty profiles. For sector 32, the duty profiles for the radar, data and tracker positions were highly correlated across the three teams (W= .95, .92, and .98, respectively). Similarly significant measures of association were obtained in sector 09 where agreement among the teams on the radar, data and tracker duties yielded W values of .88, .89, and .84, respectively.

Because of the high level of agreement within sectors across test runs and test groups, detailed analyses of the sector position duty profiles were performed on average scores. These scores were derived by transforming ratings on the 5-point scale ranging from "always my duty" to "never my duty" to numeric values of 1 to 5, respectively. Average profiles for each position at each of the two sectors are presented in tables 6 and 7.

5.3.1.1 Key Duties.

Examination of the average profiles shows that both sectors were similar in the basic duties and responsibilities assumed by the individual control positions. In all cases, the control teams departed from the traditional standard of a single controller communicating with aircraft at a sector. The teams used the two communication channels made available with the addition of Data Link by distributing communications tasks among all

TABLE 6. SECTOR 32 CONTROL POSITION DUTY PROFILE (EXPERIMENT 1)

Duty Profile: Avg. Rating 1= Always 2= Mostly 3= Occasionally 4= Rarely 5=Never

		RADAR	DATA	TRACKER
ALWAYS	1.0			
	1.1	Snt. Voice Clrnc.		
	1.2		Coord w/Team	
	1.3	Mon. Conflict		
	1.4	Cntrl. Decision		Mon.Conform.
	1.5	Mon. Conform.	Land Comm	
	1.6			Mon. Conflict
	1.7	Direct Team	Housekeep	Mon. DL Trans/ Housekeep
	1.8		F.S. Mark	
	1.9	Coord. w/ Team / Voice TOC	Mon. DL Trans.	
MOSTLY	2.0			
	2.1			DL Clrnc./ DLTOC / O/A Handoff/ Coord.w/Team
	2.2			
	2.3			
	2.4		Mon. Conflict	
	2.5			
	2.6	Mon. DL Trans.	Mon. Conform.	
	2.7		Cntrl. Decision	
	2.8			
	2.9	F.S. Mark		
OCCAS.	3.0		O/A Handoff	
	3.1	DL TOC	DL Clrnc.	
	3.2			
	3.3			
	3.4			
	3.5	O/A Handoff		Cntrl. Decision/ Direct Team/ Land Comm.
	3.6			
	3.7			
	3.8			
	3.9	Snt. DL Clrnc.	DL TOC	
RARELY	4.0			
	4.1			
	4.2			
	4.3	Land Comm.		
	4.4	Housekeep		
	4.5		Direct Team	
	4.6			
	4.7			
	4.8			
	4.9			
NEVER	5.0		Voice Clrnc./ Voice TOC	Voice TOC/ Voice Clrnc./ F.S. Mark

three controllers. In both sectors, the radar controller performed all voice communications, while the tracker and data controllers sent Data Link messages using the radar and data position keyboards.

Distributing the 14 duties from the profile to the control position that performed each most often, the radar controllers from sector 32 typically issued voice clearances, monitored for aircraft conflicts, made control

TABLE 7. SECTOR 09 CONTROL POSITION DUTY PROFILE (EXPERIMENT 2)

Duty Profile: Avg. Rating 1= Always 2= Mostly 3= Occasionally 4= Rarely 5=Never

		RADAR	DATA	TRACKER
ALWAYS	1.0	Voice Clrnc./Voice TOC		
	1.1		Housekeep	
	1.2			
	1.3		Land Comm.	
	1.4	Mon. Conflict		
	1.5	Directed Team		Mon. Conform./ Mon. DL Trans
	1.6			
	1.7	Coord w/Team/ Mon. Conform.		Mon. Conflict/ Housekeep
	1.8			
	1.9		Mon. Conflict	Coord w/ Team
MOSTLY	2.0	Contrl. Decision	Mon. Conform.	DL TOC/ DL Clrnc./ O/A Handoff
	2.1		F.S. Mark/ Coordw/Team	
	2.2			
	2.3	Mon. DL Trans.		
	2.4			
	2.5		Mon. DL Trans.	
	2.6			
	2.7	F.S. Mark	O/A Handoff	
	2.8			
	2.9			
OCCAS.	3.0			Cntrl. Decision
	3.1		DL Clrnc.	Directed Team/ Land Comm
	3.2			
	3.3		Contrl. Decision	
	3.4			
	3.5	Housekeep		
	3.6			
	3.7		Directed Team	
	3.8			
	3.9			
RARELY	4.0			
	4.1	O/A Handoff		
	4.2			
	4.3		DL TOC	
	4.4			
	4.5	DL TOC		
	4.6			
	4.7			F.S. Mark
	4.8	DL Clrnc.		Voice TOC/ Voice Clrnc.
	4.9			
NEVER	5.0	Land Comm.	Voice Clrnc./ Voice TOC	

decisions, directed other team members, and sent voice TOC messages. The data controller coordinated actions with other team members, conducted ground communications, performed sector housekeeping and marked flight strips. The tracker monitored for aircraft conformance, sent Data Link clearances and TOCs, monitored Data Link transactions and offered/accepted sector handoffs.

In sector 09, the radar controllers reported the most frequent performance of the same duties reported by sector 32 radar controllers with the addition of coordinating their actions with other team members. The data controllers performed housekeeping, ground communications and flight strip marking most often, while the trackers' most common tasks were identical to their counterparts at sector 32.

In general, these data confirm observations made during testing that the radar controllers acted as team leaders, insuring aircraft separation, making control decisions, using the radio to send voice messages, and directing associates to send Data Link messages to the aircraft. In both sectors, the bulk of the Data Link inputs were made by the tracker using the radar position keyboard and trackball.

5.3.1.2 Shared Duties.

The average ratings also indicated that a majority of duties were shared by two or more controllers. Other than carrying out voice radio communications, and marking flight strips or conducting ground communications in some cases, all tasks were performed by more than one controller. In both sectors, all three controllers noted that they shared the tasks of coordinating their actions within the team, monitoring for conflicts, monitoring aircraft conformance, and monitoring the progress and outcome of Data Link transactions "most of the time."

In addition, two controllers often shared other duties. For example, while the data controller reported marking flight strips more commonly, the radar position often shared this duty for clearances directed to the tracker for uplink. Likewise, while the tracker offered and accepted handoffs most often, the data controller typically shared this task. Although more common in sector 09, the data controller also occasionally sent Data Link clearances, and the tracker, followed by the data controller, reported sharing the tasks of making control decisions and directing the team in conjunction with the radar controller.

5.3.1.3 Teamwork.

The overall picture conveyed by the duty profiles, and confirmed during debriefing discussions, was that the addition of Data Link both demanded and promoted close team cooperation and sharing of duties. In order to make optimal use of the expanded communications channel, all three controllers shared communications tasks. This, in turn, required extensive

intercoordination among the team members, and promoted a team approach to monitoring the air traffic situation and decision making. Unlike the current voice-only ATC environment where congested voice communications place the data and tracker controllers in a relatively passive position, the use of Data Link made it possible for the team to discuss planned actions and to inform one another about actions that were taken.

The duty profiles indicate that the precise nature of the team interaction differed in the two sectors. In sector 32, all three teams that participated in the study adopted fairly fixed roles for each position to control the departure traffic. The tracker performed almost all Data Link communications with occasional assistance from the data controller at the request of the radar position.

In contrast, sector 09 used a more flexible strategy to sequence the arriving traffic. The radar controller assigned clearances to whichever associate was free to make the entries, or called out the instruction, and the available controller would make the entries.

As discussed above, both groups shared the tasks of monitoring transactions and maintaining awareness of the traffic situation among team members. This appears to have lead to sharing in the decision making and direction of others on the sector. While the radar controller was clearly the team leader in all cases, the associates in sector 09, and to a lesser extent in sector 32, often informed the radar controller that they were about to take independent actions based on a shared situation awareness and understanding of immediate task requirements. In at least one group, the radar controller reported that he was able to delegate authority to a large extent by simply instructing the data controller to "keep this group of aircraft separated' while he went on to other tasks.

5.3.2 Data Link Input Assessments.

Following each test trial in both experiments, the sector supervisors completed a questionnaire regarding their observations of the controllers' Data Link input performance (see appendix A). The questionnaire asked for a basic rating of the number of input errors that were observed ("none", "a few", or "several"). If any errors were noted, the supervisors described how the input errors were handled by the controllers.

The supervisors reported that they had observed no input errors in 13 of the 30 test runs completed by the 2 sectors. During 17 of the runs, "a few" errors were reported. In no case did the supervisors indicate that they had observed "several" input errors.

For five of the test runs in which errors had been observed, the supervisors said that the controllers had detected the error during the input process and had made the appropriate correction before sending the message. In the remaining cases, the controllers noticed the error in a Data Link message content/status display, and corrected it with a voice transmission or a second Data Link message. In no case, in either sector, did the supervisors report that the controllers detected an error only after noticing an unintended aircraft maneuver, or that the error was never detected by the controllers.

In a final questionnaire item, the supervisors made a projective evaluation of whether ATC Data Link will present a greater potential for undetected controller errors than the existing voice communications system. None of the responses from the six Atlanta ARTCC supervisors suggested that this would be the case.

5.3.3 Data Link Transaction Times.

As discussed in the description of the experimental methodology used in this study, time delays associated with uplinking a message to an aircraft and downlinking responses were based on the characteristics of a simulated Mode S transmission medium. In order to determine the precise range of transaction delay under which the findings of this study were obtained, time recordings were maintained for each Data Link transaction completed in both experiments.

The measure of delay used for analysis was Total Transaction Time (TTT). TTT is defined as the period of elapsed time from the controller's input to send the message to the appearance of a downlinked response on the controller's display. Thus, the TTT includes the technical system delays associated with uplink and downlink, and the time required by the aircrew to detect, process, and respond to the message. Since the TTT is an indicator of the overall delay experienced by the controller, it provides a generic means of examining the impact of transaction duration on ATC performance.

Figure 27 presents a frequency distribution of the TTTs obtained during this study. The distribution portrays the data in 2-second increments and includes times for the 3,699 Data Link transactions that were closed by a "wilco" or "unable" response from the pseudopilots and aircraft simulator pilots.

The truncation of the distribution to the left of the figure clearly reflects the minimum technical delays of the transmission medium, with no TTTs below the range of 6.1 to 8 seconds. Within the range of 6.1 to 20 seconds, the TTTs appear to be normally distributed. The rapid drop in the frequency of TTTs above 20 seconds identifies those cases where the time taken for the aircrew to respond delayed the downlink until the next available Mode S antenna scan.

The full distribution of recorded TTTs ranged from 6.1 to 60 seconds. The mean TTT was 15.96 seconds with a standard deviation of 6.83 seconds. Of the total number of transactions, approximately 83 percent had TTTs below 20 seconds. An additional 13 percent were within the range of 20.1 to 30 seconds. Only 4 percent of the transactions took more than 30 seconds to complete.

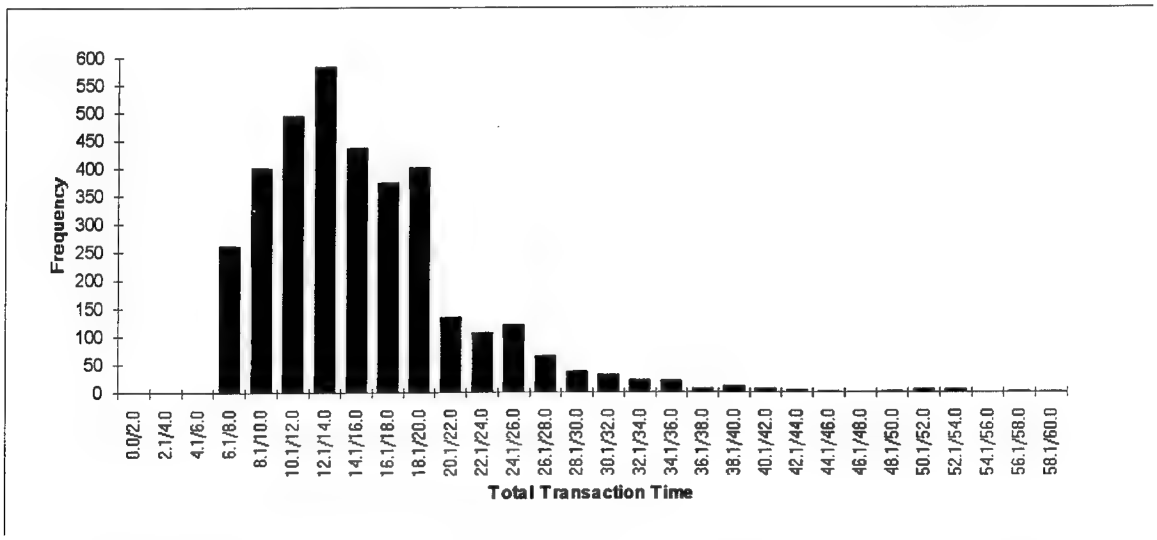

FIGURE 27. TOTAL TRANSACTION TIME FOR 3699 DATA LINK MESSAGES SENT IN EXPERIMENTS 1 AND 2

5.4 DEBRIEFING.

Debriefing sessions were conducted at the conclusion of each of the three replications of the study. The controllers and supervisors from both test sectors participated in combined groups. Each group was asked to comment on the quality of the simulation, the impact of Data Link ATC communications in an operational environment, control team procedures, and requirements for the Data Link controller interface. The findings of the three debriefing sessions are combined and organized by topic in the following subsections.

5.4.1 Simulation Fidelity.

The initial question addressed by the participants was whether they felt that the simulation had been sufficiently realistic, and if the Data Link system would work as well in the operational sectors as it did during testing. Twenty-three of the 24 participants (18 controllers and 6 supervisors) indicated that the experiments provided a fair test of Data Link effectiveness in the Atlanta ARTCC sectors that were simulated. The group also agreed that the system would work as well, or better, in the operational environment.

One of the data controllers from sector 32 noted that, since the baseline day lacked weather and some of the ground communications which can complicate ATC tasks, his workload during the simulation may not have been equivalent to that at the test sector in some instances. However, this individual also indicated that he felt that the Data Link services (especially TOC) would help controllers at the operational sector.

Other participants from both sectors in two debriefing sessions suggested that the positive effects that Data Link communications would have on sector performance in the real-world were underestimated during the simulation. These individuals noted that some characteristics of the simulation made the task of controlling the traffic more difficult than it would have been at the operational sectors. Included among these were the fact that the simulator and pseudopilots could not be as responsive to control instructions as pilots who tend to be highly familiar with the ATC procedures in the airspace that they traverse on a regular basis. In addition, the controllers noted that surrounding sectors in the operational environment would have provided more assistance by coordinating traffic and providing better spacing for the aircraft entering the subject sectors.

They suggested that these factors made the test a conservative evaluation of the extent to which Data Link would improve sector efficiency.

5.4.2 Data Link Effects on Controllers and on Service to Users.

Based on their experience during simulation testing, the controllers and supervisors were asked to predict whether Data Link would be an asset if implemented today and, if so, to describe its impact on controllers and the quality of service to NAS users. The participants unanimously agreed that Data Link would improve the effectiveness of ATC operations. The direct effects on controllers that were mentioned included (1) a more orderly work situation during traffic rushes, (2) the ability to transmit more information in the same period of time, (3) an improved distribution of workload at the sector and greater productivity, (4) more timely and effective issuance of critical voice clearances due to reduced frequency congestion, and (5) reduced communications errors.

In addition, participants in all three sessions noted that Data Link would have a profound effect on team communication and effectiveness. They noted that during heavy traffic periods using only voice radio, the radar controller may be engaging in non-stop communications. With Data Link, they indicated that the control team is able to work together to resolve the traffic problem and share the workload. The data controller and tracker are much more aware of the traffic picture and involved in the task of safely expediting aircraft progress. The radar controller has the time to communicate his plan, making his associates more able to share in its execution and detect when changes in the plan are needed.

Participants in two of the sessions suggested that one of the indirect effects of Data Link implementation on the ATC system would be a reduction in sector staffing requirements. These comments indicated that the increased communications capacity provided by Data Link would make it possible to avoid the practice of splitting sectors since this measure is often employed when frequency congestion is excessive. In addition, it was noted that adding a second or third controller to support a busy sector could be avoided or delayed with the availability of Data Link.

All 24 participants agreed that the impact of Data Link on ATC performance would enhance service to NAS users. Specific effects mentioned by the controllers that would improve aircraft operating efficiency included (1) the receipt of more timely control clearances resulting in fewer maneuvers and path changes, (2) reduced use of holding

patterns, (3) more efficient vectoring, and (4) more fuel efficient descent and climb profiles.

5.4.3 Data Link Transaction Delays.

The debriefing participants also were asked to reflect on their simulation experiences in order to comment on any negative effects of Data Link transaction delays. The subjects reported that delays were not a problem during testing. However, several suggested that transaction delays could limit Data Link's utility if they were excessive. Participants in two sessions indicated that the effects of delays that they experienced were outweighed by the increased ability to send a voice message when needed on the clear radio channel.

A typical comment from controllers during each of the debriefing sessions was the rapidity at which they adapted to Data Link delays during training. When asked to describe the skills that were acquired, the controllers noted that they quickly learned to judge when a clearance should be sent by voice rather than Data Link (e.g., a critical turn into the arrival traffic sequence). They also indicated that they learned to send Data Link clearances in a more anticipatory fashion to achieve the desired result.

5.4.4 Performance Issues and Design Recommendations.

The controllers identified two problems when asked to identify potential sources of error in the use of Data Link. While they agreed that typing errors were possible with Data Link, the controllers indicated that such errors would tend to be corrected before the message is sent when observed in the message composition area, or in the Data Link status displays after the uplink had occurred. However, it was suggested that for input errors to be corrected consistently, the controller making the inputs would require easily accessible feedback on message content. The controllers noted that the composition area and message status list on the PVD were not always directly viewable by the data or tracker positions located to the left and right of the PVD display.

A second potential problem noted by the controllers was the possibility of forgetting whether a message had been sent, or the precise contents of a message after a transaction had been closed and the message content and status displays were cleared. They did not indicate that forgetting was any more of a problem with Data Link than with the existing voice system.

However, the controllers did agree that the problem should be addressable with Data Link by maintaining a recallable list of past messages.

Based on a discussion of the issues outlined above, the controllers offered two unanimous recommendations for modifications to the design of the Data Link controller interface. First, easily viewable feedback displays should be provided for associate controllers engaged in entering and monitoring Data Link messages. Such displays should include a feedback display showing the message content as it is entered, as well as a message status list. In the current Host/PVD system, these might be presented on the data position Computer Readout Display (CRD) unit.

Second, a Data Link history list should be provided. This list should be available on command for each aircraft and present the last clearance message of each type (i.e., altitude, heading, and speed). The controllers indicated that the history list would be required where control teams rather than a single controller staffs a sector. In these situations, the history list would resolve any question of whether a message had been sent by a team member, eliminate unnecessary discussion, and prevent instances where a message is sent to an aircraft twice to ensure its receipt.

Additional recommendations for system enhancements included an ability to send turn clearances in degrees of heading change, the capability to save and reuse free text messages, and a preloaded standard initial clearance that could be sent to an aircraft entering the sector automatically when it wilcos the TOC from the sending controller.

5.4.5 Controller Team Procedures and Information Requirements.

A final topic discussed during the debriefing sessions was Data Link's implications for sector operations and controller information requirements. There was unanimous agreement among the participants that multi-controller operation takes maximum advantage of the increased communications capacity provided by Data Link. However, they also noted that the control/communications team concept will require development of new procedural guidelines for sector operation and accommodation of new information needs of the team members.

Each control team in this study independently developed and tested procedures for distributing communications duties and other sector responsibilities during training. As discussed in section 5.3.1, this resulted in the adoption of some operating rules that were common across the

teams, as well as variations unique to individual teams. The successful outcome of both experiments suggests that the teams effectively applied these procedures during testing to achieve safe ATC operations with reduced aircraft delays and increased operating efficiency.

During debriefing, the participants indicated that the addition of Data Link provided an opportunity to effectively implement a "radar team" concept. However, they also noted that standardized, but flexible procedural guidelines will be needed in the future to ensure that two and three member control teams will be optimally productive and efficient in the use of Data Link. Such guidelines should define position responsibilities and intercoordination requirements for team members. In addition, training in team work may be needed to promote effective interaction among individual controllers who rotate through different team assignments.

The participants also argued that distributing communications tasks among multiple controllers will modify the information requirements of individual control positions. As noted in the previous section, these requirements will include the addition of displays for associate controllers to evaluate the accuracy of their inputs and monitor transactions, and provision of a history list function to promote team coordination and support short term memory limitations. Finally, while not technically feasible in the current en route workstation, the participants noted that enhancing the controller interface by providing the radar position with a third keyboard/trackball would permit all members of a three-controller team to make Data Link entries.

6. BENEFIT ESTIMATION AND AGGREGATION.

The primary objective of this study was to identify and measure some of the benefits that the implementation of two-way Data Link ATC communications would provide to NAS users. The results of the two experiments presented in section 5 of this report objectively demonstrated that controllers using two-way Data Link were able to provide ATC services that improved en route sector productivity and efficiency. These effects were reflected in reduced aircraft ground delay, flight time, and flight distance in comparison to a current operational environment using only voice radio communications.

Estimating the economic cost savings associated with these findings provides one approach to determining the potential magnitude of two-way Data Link's impact and its significance to NAS users. The following

subsections present annualized user cost savings estimates for the local Atlanta ARTCC sectors tested in the experiments, and for a group of en route sectors across the U.S. where operations are adversely affected by similar limitations in ATC communications capabilities.

6.1 LOCAL ATLANTA ARTCC BENEFIT ESTIMATE.

Measures of the time savings achieved by aircraft in both experiments of this study were used as the basis for calculating associated cost savings in the Atlanta ARTCC. Time savings were expressed in decimal minutes for each category of air traffic represented on the historical baseline day. Table 8 summarizes the ground and airborne time in sector savings obtained during testing with Data Link. The ground delay savings presented in the table are the total minutes for all affected aircraft at the Atlanta airport achieved by eliminating restrictions on aircraft entering sector 32. In-flight savings for the two sectors are averages for the test control teams in the three replications of each experiment.

Estimates of the user costs associated with these results were computed according to Office of Management and Budget (OMB)-approved practices.

TABLE 8. TOTAL GROUND DELAY AND SECTOR FLIGHT TIME SAVINGS FROM EXPERIMENTS 1 AND 2

Air Traffic Category	Number of Aircraft	Total Minutes Saved
Atlanta Ground Delayed	48	1108.00
Sector 32 Atlanta Departures	24	49.44
Sector 32 Charlotte Departures	4	5.16
Sector 32 Overflights	13	14.69
Sector 09 Atlanta Arrivals	23	95.45
Sector 09 Peachtree Dekalb Arrivals	3	.15
Sector 09 Overflights	14	29.26

Per-minute operating costs were based on data obtained from the most recent update of the FAA Guide for Economic Analysis of Investment and Regulatory Decisions (FAA, 1994). This document lists average aircraft operating costs weighted by the hours of use over a range of sizes and types of aircraft. For commercial air carriers, the taxi (ground delay) rate is $26.20 per minute. The airborne rate is $31.50 per minute.

These rates for the "air carrier fleet" represent averages for equipment ranging from 4-engine, wide body, turbofan aircraft to two-engine, piston aircraft. All aircraft that were flown through the Atlanta ARTCC sectors during the test periods of the two experiments in this study are included in this category. The rates are conservatively based on average block-to-block costs including the value of fuel, maintenance, rent, crew salaries, and other direct costs to air carriers. They do not include estimates of the value of passenger time loss resulting from delays.

Based on these rates, the 1,108 minutes of ground delay savings demonstrated in experiment 1 equates to a dollar cost savings with Data Link communications of $29,029. The total of 194.15 minutes of in-flight time savings produced in both experiments yields a cost savings of $6116. In both cases, these savings refer only to the two sectors over the tested peak traffic periods on a single day.

Annual savings estimates for these traffic rush periods were based on reports of the frequency with which the two sectors experience the tested saturation problems. In both cases, Atlanta ARTCC personnel indicated that these problems occurred on a daily basis throughout the year. In order to produce a conservative estimate of annual costs, all Saturdays and five major holidays were disregarded in the analysis. The remaining period of 308 days was discounted by an additional 20 percent to account for daily variations in traffic demand, leaving a final total of 246 problem days for the two rush periods in sectors 32 and 09.

Predictions of annual cost savings were based on the product of the daily savings estimates and the number of days of problem occurrence. Accordingly, the cost savings attributable to reduced ground delays for the tested Atlanta sector were estimated at $7,141,282. The predicted combined sector savings for reduced flight time were $1,504,468. Thus, the total estimated annual cost savings are $8,645,750 for the two sectors in the Atlanta ARTCC.

It should be noted that both sector 32 and sector 09 experience rush periods at other times of day not tested in the present experiments. Thus, these values represent a conservative estimate of the total annual savings that would be achieved with Data Link at Atlanta.

6.2 NATIONAL BENEFIT ESTIMATE.

6.2.1 National Sector Survey.

A national sector survey was conducted as a basis for producing an estimate of the annualized national economic gains that would be associated with the results of this study (FAA Technical Center, 1994). The purpose of the survey was to identify and gather data on en route airspace sectors throughout the NAS which experience inefficiencies attributable to communications problems similar to those found in the Atlanta ARTCC sectors tested in the study. Specifically, the target sectors for the survey were those which experience volume saturation associated with frequency congestion and require assistance (e.g., MIT restrictions, aircraft reroutes, and additional staffing).

Telephone interviews were conducted with Traffic Management Unit (TMU) personnel from 20 ARTCCs. The three en route facilities not included in the survey were Anchorage, Honolulu, and San Juan. After explaining the purpose of the survey, the TMU managers were asked whether their facility contained any sectors which fit the target sector definition. If one or more sectors were identified, the interviewer asked the manager to answer the following series of questions about each sector:

Sector Identification - What is the sector number, sector identifier, sector altitude limits, and area within the ARTCC where the sector is located?

Traffic Types - What categories of air traffic transition through the sector?

Sector Workload and Reroutes - How busy is the sector and what level of saturation does it experience? What control techniques are employed to transition the aircraft? Are trackers or coordinators used regularly? If so, how many times each day? Do controllers ever hold aircraft because of sector saturation? Does TMU ever reroute aircraft around the sector to reduce saturation?

TMU Restrictions - If MIT restrictions are implemented to reduce saturation or frequency congestion in the sector, what facilities are being affected by the flow and what is the specific flow restriction?

Forty-one additional target sectors were identified whose problem profiles closely resembled those of the two Atlanta ARTCC test sectors. A second telephone survey of the TMU personnel responsible for the target sectors was completed to obtain additional quantitative data for use in the methodology developed for computing national benefits. For each sector, the interviewee was asked to (1) identify the number of days per year that the problem is experienced, (2) specify the daily time period during which the problem occurs, and (3) express the nature of the air traffic situation during the peak rush period by estimating the extent to which the sector's problems are associated with departures, arrivals, and overflights.

6.2.2 National Benefit Estimation Methodology.

Because intensive laboratory testing of each of the survey target sectors was not economically feasible, an analytical approach was used to extend the results of the present study to a national level by extrapolation, comparison, and statistical analysis. Detailed equations used in the computation of economic benefits are presented in appendix B. The following paragraphs summarize the methodology in narrative form.

The process of estimating benefits began with an analysis of the comparability of the sector saturation problems experienced in the Atlanta ARTCC test sectors to the 41 additional target sectors identified by the national sector survey. The two test sectors in which efficiency improvements were observed with the introduction of Data Link can be classified as transitional sections of airspace in which groups of aircraft are moving between flight phases. The communications and control problems in the sectors are associated with three archetypal configurations of air traffic flow. In Atlanta's sector 32, communication limitations adversely affect the ability to effectively control masses of aircraft departing from an airport that must be climbed and separated on common and diverging routes. In sector 09, several streams of arrival traffic must be sequenced and merged over an arrival fix. The communications frequency congestion problems in both sectors are complicated by crossing overflight traffic.

The similarity of the problems experienced by the target survey sectors to those of the test sectors was quantified by comparing their traffic configurations to these archetypes. As noted in section 6.2.1, TMU

personnel from the survey ARTCCs provided expert judgments of sector traffic configuration by estimating the extent to which the air traffic in each rush period could be classified as a departure problem, an arrival problem and an overflight problem. Each sector was characterized by its comparability profile expressed as percent arrival, departure, and overflight (e.g., 80 percent Arrival, 15 percent Departure, 5 percent Overflight).

In performing the benefit calculation, these profiles were used to determine the magnitude of the airborne delay savings obtained in the experiments that would be attributed to each sector. Average airborne delay savings for the test sectors were calculated for each category of air traffic that flew in the two Atlanta scenarios. A per-aircraft savings for arrivals of 4.15 minutes was based on the reduction in delay obtained for Atlanta arrivals with the baseline traffic in experiment 2, averaged over the three test controller teams. The per aircraft savings for departures of 2.06 minutes was based on the average reduction in airborne delay for the baseline Atlanta departures in experiment 1. The savings for overflight aircraft of 1.63 minutes was based on a weighted average reduction in airborne delay for the overflight aircraft in baseline test runs from both experiments.

The per-aircraft airborne delay savings for each survey sector problem period was computed by multiplying the sector's comparability profile by the associated delay savings, and summing the products. Using the example above, the sector with a 80 percent arrival, 15 percent departure and 5 percent overflight profile would yield a savings of $.8(4.15)+.15(2.06)+.05(1.63) = 3.71$ air minutes per aircraft.

Total airborne delay savings for a survey sector problem period were computed by multiplying the traffic count by the per-aircraft savings. The FAA's Enhanced Traffic Management System (ETMS) was used to obtain exact counts of the number of affected aircraft in the survey sectors during each problem period. Traffic count data in consecutive 15-minute periods for a single day were obtained from the ETMS for each target sector. The data were searched to determine sector aircraft counts for the problem periods identified by the TMUs in the sector survey. In the example, with a traffic count of 30 aircraft, the total in-flight savings for the sector would be 111.3 minutes.

Savings attributable to reduced ground delays were based on the average, per-aircraft time savings calculated for each MIT restriction tested in

experiment 1. Assuming an ability to eliminate restrictions with Data Link, the applied savings for a sector enforcing a 20 MIT, 15 MIT or 10 MIT restriction were 23.08, 12.52, and 2.56 minutes, respectively. These savings were extended only to those sectors for which the national sector survey respondees reported that MIT restrictions on departures for entering the sector were regularly enforced during the rush period. If a sector was reported as applying a range of restrictions over the period (e.g., 10-15 MIT), the average aircraft savings associated with the lower restriction was applied. If the sector has floating restrictions, no ground delay benefit was applied.

Ground delay savings for each problem period were computed by multiplying the per-aircraft savings from the experiment by the problem profile percentage for departures, and by the total number of aircraft in the sector. Thus, assuming a 20 MIT restriction in the example sector, this formula yields a daily savings of .15(23.08)30 = 103.86 minutes saved in ground delays. It should be noted that the estimates produced in this manner were conservative because they did not include the ground delay savings to aircraft in the departure queue which do not enter a survey sector.

The projected annual delay savings for each sector were computed by multiplying the in-flight and ground delay daily estimates by the number of days per year that the survey respondees reported that the problem occurs. In cases where respondees indicated that the problem was a daily occurrence throughout the year, a conservative estimate was used by disregarding all Saturdays and five major holidays. Thus, the maximum possible number of problem days was 308.

Total monetary savings for each sector problem period were calculated by multiplying the annual minutes of in-flight and ground delay savings for each sector by the FAA per-minute dollar cost rates cited in section 6.1. For commercial air carriers, the current taxi (ground delay) rate that was applied was $26.20 per minute. The airborne rate was $31.50 per minute.

6.2.3 National Results.

Detailed delay and cost savings results for the individual en route sectors included in the national benefit estimate are presented in appendix B. In summary, the data indicate that ATC performance inefficiencies associated with the inherent limitations of the broadcast voice radio communications system affect 9,679 flights each day in the 43 target sectors. According to the

calculations performed for this study, these inefficiencies are responsible for a total of 7,980 24-hour days of aircraft delay each year (11,491,387 minutes) that could be eliminated with the implementation of two-way Data Link ATC communications. This is equivalent to eliminating delays on each of the affected flights by one-half day in the air, and one-third day on the ground each year. As shown in appendix B, the total estimated annual cost savings for NAS users would be over 337 million dollars.

Examination of appendix B shows that these benefits would be distributed throughout the target sectors and ARTCCs. The two sectors with the highest potential costs savings are located in the Chicago and Indianapolis ARTCCs. Both of these sectors process approximately 500 aircraft during the daily problem periods identified in the national sector survey. Together, they account for 1,583 aircraft-days of delay each year. The combined estimated savings with Data Link implementation for flights in these sectors is over 63 million dollars annually.

In the context of overall NAS operations, the 43 target sectors represent approximately 7 percent of the total number of domestic en route airspace sectors. Discounting any flights that traverse more than one congested sector, the 9,679 affected flights comprise approximately 10 percent of the average daily number of flights to large, medium, and small hub airports in the U.S. (FAA, 1993).

Table 9 contrasts the annual cost savings projected for two-way Data Link in the 43 en route sectors to an independent estimate of current airline operating losses. The table presents data from a recent Air Transport Association (ATA) analysis which indicated that annual airline losses caused by ATC and airspace inefficiencies are approximately \$3.5 billion (Swierenga, 1994). As shown in the table, the outbound taxi delay and en route loss categories that were addressed in this study make up a majority of the total airline losses due to ATC inefficiencies (74 percent).

The benefit estimates for these categories indicate that Data Link would reduce outbound taxi delay dollar losses by 9.9 percent, and en route losses by 15.8 percent. The total benefit estimate attributable to the en route sectors where Data Link would be expected to expand the capacity of the ATC communications channel and alleviate related inefficiencies is approximately 10 percent of the total ATA annual loss estimate.

TABLE 9. COMPARISON OF ANNUAL DATA LINK BENEFIT ESTIMATE TO ATA ESTIMATES OF AIRLINE LOSSES FROM ATC AND AIRSPACE INEFFICIENCIES

Delay Category	**ATA Estimate of Annual Airline Losses**	**Estimated En Route Annual Data Link Savings**
Gate Delays		
Flow Control	$ 95,137,222	
Air Traffic	$ 73,902,504	
Airport	$ 7,390,226	
Taxi Delays		
Outbound	**$ 1,215,547,622**	**$ 119,790,977**
Inbound	$ 361,034,841	
En Route Losses		**$ 217,955,195**
Indirect Routes	**$ 1,282,705,520**	
Execution and Delays	**$ 97,308,764**	
Cruise Inefficiency	$ 72,741,148	
Weather	$ 28,696,818	
TOTAL	**$ 3,492,737,393**	**$ 337,746,172**

In evaluating the reliability of the benefit projections discussed above, it should be noted that extensive measures were taken to minimize the probability of overestimating actual cost savings. These measures included the use of objective data from an operational ATC facility and from extremely high fidelity, manned simulation research as the basis for calculating savings. In addition, conservative options were consistently adopted when screening sectors for inclusion in the national calculation, and when selecting the time periods and number of flights to which benefits were extended.

In particular, it should be remembered that this study addressed only one dimension of Data Link's potential benefit. The estimated cost savings are restricted to Data Link's ability to increase ATC communications capacity in a single domain of ATC operations. Safety and efficiency enhancements that may result from two-way Data Link's capability to improve the accuracy of communications, and from its use in other ATC environments are expected to significantly increase estimated cost savings to aircraft owners and operators.

7. CONCLUSIONS.

The results of the study presented in this report support the following conclusions regarding the effects of domestic, two-way Data Link Air Traffic Control (ATC) services on flight delays, flight efficiency, and associated National Airspace System (NAS) user costs.

a. The real-time, manned simulation experiments performed for this study indicate that the implementation of two-way Data Link ATC services in an en route ATC environment can significantly reduce flight delays and operating inefficiencies. The study supported the hypothesis that supplementing the voice radio communications system with Data Link in two operational airspace sectors in the Atlanta Air Route Traffic Control Center (ARTCC) alleviated sector saturation problems that are experienced on a regular basis. Specific conclusions drawn from the experiments are outlined below.

1. Data Link permitted the elimination of spacing restrictions that are enforced to prevent saturation in a departure sector. This resulted in a 62 percent reduction in ground delays for departing aircraft.

2. The implementation of Data Link significantly enhanced sector throughput and flight efficiency. In both the departure and arrival sectors, average flight times and distances were reduced by approximately 20 percent. These improvements were associated with more efficient climb profiles for departures and the elimination of aircraft holding patterns and inefficient vectoring for arrivals.

3. The study showed that controllers using Data Link also were able to maintain more efficient control of the sector traffic when the number of departure and arrival aircraft were increased by 10 to 40 percent over current traffic levels. In addition, the data suggest that the rate of growth in aircraft delays with increased traffic levels representative of future airspace demands would be significantly curtailed with Data Link in comparison to a voice-only communications environment.

4. The evidence for user benefits obtained in the experiments was validated by multiple supplementary criteria. As indicated by measures of aircraft separation, and operational assessments by ATC supervisors, controllers and pilots, all test runs were completed with a margin of safety which equaled, or exceeded typical levels observed in the operational sectors. Controller performance on key sector tasks was unanimously graded by ATC

supervisors as being within normal limits, or better. Furthermore, controller ratings and measures of handoff latency yielded no evidence of excessive controller workload with Data Link.

b. The current operational inefficiencies of both sectors examined in this study are caused by limitations on controller abilities to communicate effectively with aircraft in a congested voice radio environment. The benefits that were recorded in the experiments were a direct result of the increased communications capacity made possible by adding Data Link to the existing voice channel.

The findings of the study indicate that resulting improvements in sector productivity and in ATC service to aircraft were attributable to three primary factors. First, Data Link alleviated frequency congestion, making the voice radio consistently available for time-critical clearance delivery. Second, a majority of standard clearances and other repetitive messages were sent using simplified Data Link inputs, thereby freeing the controllers to devote more time to developing and executing effective control strategies. Finally, optimal use of the expanded communications capability was achieved by distributing communications tasks to all members of the control teams. This permitted simultaneous messaging to different aircraft. It also allowed the controllers to act as coordinated and flexible team decision makers.

c. Direct computation of the annual dollar value associated with the performance results obtained for the sectors during the two, peak traffic periods tested in the study yielded evidence for significant user cost savings. Total annual savings attributable to the reduced ground delays and flight times demonstrated with Data Link exceeded $8.6 million for the two sectors at the Atlanta ARTCC.

d. It is very probable that the efficiency problems addressed in this study and the observed impact of Data Link extend beyond the two Atlanta ARTCC sectors that were tested. A national sector survey conducted in conjunction with the study shows that at least 41 additional en route sectors across the U.S. experience similar, communications-related saturation problems during one or more daily periods of peak traffic. The survey indicates that over 9,600 flights annually experience significant airborne and/or ground delays caused by communications limitations in these sectors. Benefit estimates which extended the results of the study to the survey sectors show that these flights would achieve a total of over $337 million in operating cost savings annually with the introduction of two-way Data Link ATC communications.

8. RECOMMENDATIONS.

The following recommendations for future actions by the Federal Aviation Administration (FAA) and by aircraft owners and operators are based on the results and conclusions derived from this study.

a. This study produced data which show that the implementation of domestic, two-way Data Link communications will result in significantly improved Air Traffic Control (ATC) service and reduced aircraft operating expense. The extent to which such benefits will be realized in the National Airspace System (NAS) will depend on the number of aircraft that are equipped with the necessary Data Link avionics systems. Consequently, it is recommended that aircraft owners and operators consider the findings of this study as they perform cost-benefit analyses in support of any decision to invest in the capability to receive two-way Data Link ATC services.

b. Two-way Data Link is expected to directly impact the quality of ATC operations by increasing the capacity of the controller-pilot communications channel and by improving the accuracy of air-ground communications. The benefits and estimated cost savings demonstrated in this study are associated only with the ability of Data Link to increase communications channel capacity in a single domain of ATC operations. Safety and efficiency enhancements that may result from two-way Data Link's capability to improve the accuracy of communications, and from its use in other ATC environments are likely to significantly increase estimated cost savings to aircraft owners and operators. For this reason, it is recommended that the FAA conduct research to obtain evidence for these additional benefits and to estimate the magnitude of related cost savings.

9. REFERENCES.

Billings, C.E. and Reynard, W.D., Dimensions of the Information Transfer Problem. In C.E. Billings and E.S. Cheaney (Eds.) *Information Transfer Problems in the Aviation System.* NASA Technical Paper 1875, National Aeronautics and Space Administration, 9-13, 1981.

Data Link Development Team, *Controller Evaluation of Initial Data Link Terminal Air Traffic Control Services: Mini Study 1.* Final Report, DOT/FAA/CT-90/29, 1991.

Aviation Industry - A Call to Action. Federal Aviation Administration, 1988.

1993 Terminal Area Forecast. Federal Aviation Administration, FAA-APO-93-9.

Economic Analysis of Investment and Regulatory Decisions - A Guide. Federal Aviation Administration, FAA-APO, First Quarter, 1994.

Data Link Airline Benefits Study National Sector Survey. Airborne Collision Avoidance and Data System Division, Research Directorate for Aviation Technology, Federal Aviation Administration Technical Center, DOT/FAA/CT-ACD320 94/2, 1994.

Data Link: En Route Controller Operational Training Manual. Communication/Navigation/Surveilance Service, Data Link Division, Federal Aviation Administration Technical Center, FAATC/ACW500-L98, 1995.

Data Link Benefits Study SIMMOD Simulation Final Report. Report produced under the direction of FAA Operations Research, AOR 100. LeTech, Inc., 1995.

Norman, D.A. and Bobrow, D.G. On Data-Limited and Resource-Limited Processes. *Cognitive Psychology*, 7, 44-64, 1975.

RTCA *Minimum Operational Performance Standards for ATC Two Way Data Link Communications.* Document No. RTCA/DO-219, RTCA Special Committee 169, August 27, 1993.

Shingledecker, C.A. and Talotta, N.J. *Controller Workload Assessment in the Development of Data Link Air Traffic Control Services.* Proceedings of the Conference on Workload Assessment and Safety, Royal Aeronautical Society, 1993.

Swierenga, D. *Estimates of Airline Losses From ATC and Airspace Inefficiencies.* Briefing Documentation, Air Transport Association, 1994.

Talotta, et. al. *Operational Evaluation of Initial Data Link Air Traffic Control Services.* Final Report, DOT/FAA/CT-90/1, Federal Aviation Administration Technical Center, 1990.

APPENDIX A

ASSESSMENT INSTRUMENTS

DATA LINK BENEFITS STUDY
SUPERVISOR QUESTIONNAIRE

Part I. Performance Ratings

Please evaluate the ATC operations observed during this test run on the following factors:

---

1. Errors or omissions in required flight strip marking.

   a) _____ Never Occurred

   b) _____ Rarely Occurred

   c) _____ Occurred, But Within Normal Limits of Operational Acceptability

   d) _____ Occurred More Often Than Normal For This Sector At This Time of Day

   e) _____ Occurred <u>Unacceptably</u> Often

2. Gave Arriving Aircraft Inefficient (Early) Descent.

   a) _____ Never Occurred

   b) _____ Rarely Occurred

   c) _____ Occurred, But Within Normal Limits of Operational Acceptability

   d) _____ Occurred More Often Than Normal For This Sector At This Time of Day

   e) _____ Occurred <u>Unacceptably</u> Often

3. Gave Departing Aircraft Inefficient (Late) Climb.

   a) _____ Never Occurred

   b) _____ Rarely Occurred

   c) _____ Occurred, But Within Normal Limits of Operational Acceptability

   d) _____ Occurred More Often Than Normal For This Sector At This Time of Day

   e) _____ Occurred <u>Unacceptably</u> Often.

4. Issued Clearances Later or Earlier Than Appropriate.

    a) ______ Never Occurred

    b) ______ Rarely Occurred

    c) ______ Occurred, But Within Normal Limits of Operational Acceptability

    d) ______ Occurred More Often Than Normal For This Sector At This Time of Day

    e) ______ Occurred <u>Unacceptably</u> Often

5. Failed to Comply with Letters of Agreement.

    a) ______ Never Occurred

    b) ______ Rarely Occurred

    c) ______ Occurred, But Within Normal Limits of Operational Acceptability

    d) ______ Occurred More Often Than Normal For This Sector At This Time of Day

    e) ______ Occurred <u>Unacceptably</u> Often

6. Offered Hand-Offs Earlier Than Appropriate.

    a) ______ Never Occurred

    b) ______ Rarely Occurred

    c) ______ Occurred, But Within Normal Limits of Operational Acceptability

    d) ______ Occurred More Often Than Normal For This Sector At This Time of Day

    e) ______ Occurred <u>Unacceptably</u> Often

7. Offered Hand-Offs Later Than Appropriate.

    a) ______ Never Occurred

    b) ______ Rarely Occurred

    c) ______ Occurred, But Within Normal Limits of Operational Acceptability

    d) ______ Occurred More Often Than Normal For This Sector At This Time of Day

    e) ______ Occurred <u>Unacceptably</u> Often

8. Accepted Hand-Offs Later Than Appropriate.

a) _____ Never Occurred

b) _____ Rarely Occurred

c) _____ Occurred, But Within Normal Limits of Operational Acceptability

d) _____ Occurred More Often Than Normal For This Sector At This Time of Day

e) _____ Occurred <u>Unacceptably</u> Often

9. Failed To Meet Miles-In-Trail Restrictions That Were In Force During The Test Run.

a) _____ Never Occurred

b) _____ Rarely Occurred

c) _____ Occurred, But Within Normal Limits of Operational Acceptability

d) _____ Occurred More Often Than Normal For This Sector At This Time of Day

e) _____ Occurred <u>Unacceptably</u> Often

Part II. Overall Operational Assessment

Please use the scale below to make an overall operational assessment of ATC performance during this test run:

a) _____ The margin of safety was higher than normal for operations at this sector at the Atlanta ARTCC.

b) _____ Operations were typical for this sector, with acceptable safety.

c) _____ Operational safety was not compromised, but I had safety concerns.

d) _____ Operations were unsafe, and unacceptable.

If you checked c. or d., please explain your rating below. Thoroughly describe the incidents or factors which influenced your judgment.

Part III. Data Link Usage

1. Did you observe any input errors in selecting or entering Data Link messages?

   a) ______ I did not notice any input errors.

   b) ______ I noticed a few errors.

   c) ______ The controllers made several errors.

2. If you observed Data Link entry errors, how were they handled? (Check all that apply)

   a) ______ Errors were detected by the controllers during the input process and corrected before sending.

   b) ______ The controllers noticed the error in the FDB or Status List Display after sending the message. The error was corrected by voice radio or a new Data Link message.

   c) ______ The error was detected only by noticing an unintended aircraft maneuver.

   d) ______ The error was never detected by the controllers.

3. From your observations, do you feel that Data Link communications will present a significantly greater potential for undetected controller error than voice communications in an operational environment?

DATA LINK BENEFITS STUDY
CONTROLLER QUESTIONNAIRE

Part I. Position Duties and Workload

1. **Duty Description** -- *Please indicate the extent to which you performed each of the following tasks at your position during this test run. For each duty, place an "x" in the column that best describes your level of task involvement.*

	Always My Duty	Mostly My Duty	Occasionally My Duty	Rarely My Duty	Never My Duty
Issued ATC Clearances Using Voice Radio	____	____	____	____	____
Issued ATC Clearances Using Data Link	____	____	____	____	____
Offered/Accepted Sector Handoffs	____	____	____	____	____
Sent TOC Messages Using Voice Radio	____	____	____	____	____
Sent TOC Messages Using Data Link	____	____	____	____	____
Marked Flight Strips	____	____	____	____	____
Monitored PVD for Aircraft Conformance	____	____	____	____	____
Monitored PVD for Aircraft Conflicts	____	____	____	____	____
Monitored Data Link Transactions	____	____	____	____	____
Handled Land Line Communications	____	____	____	____	____
Directed Others on Control Team	____	____	____	____	____
Made Control Decisions	____	____	____	____	____

Coordinated My Actions With Other Team Members	_____	_____	_____	_____	_____
Performed Sector "Housekeeping"	_____	_____	_____	_____	_____
Other Duties (Describe Below)	_____	_____	_____	_____	_____

2. **Workload Rating** -- *Please use the scale below to rate the level of workload that you experienced at your position during this test run. This should be a rating of your personal perception of how hard you had to work to perform your duties -- not an estimate of overall sector loading or traffic count. Place an "x" in the space next to the phrase which best describes your perceived workload.*

In comparison to a corresponding work period at this sector in the facility, the workload at my position during this test run was:

_____ Much Lower Than Usual

_____ Somewhat Lower Than Usual

_____ About The Same

_____ Somewhat Higher Than Usual

_____ Much Higher Than Usual

Please describe any factors that you feel may have influenced your perceived workload:

Part II. Overall Operational Assessment

Please use the scale below to make an overall operational assessment of ATC performance at your sector during this test run:

a) _____ The margin of safety was higher than normal for operations at this sector at the Atlanta ARTCC.

b) _____ Operations were typical for this sector, with acceptable safety.

c) _____ Operational safety was not compromised, but I had safety concerns.

d) _____ Operations were unsafe, and unacceptable.

DATA LINK BENEFITS STUDY
PILOT SAFETY QUESTIONNAIRE

What is your opinion about the safety of the flight you just completed?

1	2	3	4	5	6	7
Completely Safe						Completely Unsafe

Please explain any factors that affected the safety of this flight:

APPENDIX B

NATIONAL BENEFIT CALCULATIONS

NATIONAL ESTIMATION EQUATIONS

Subscripts indicate the identity of the reference case sector or of the configuration.

Step one: computing benefits from baseline sectors

1a. $B_{A9} = \dfrac{\text{Arrival air minutes saved}}{\text{Arrival aircraft}_9}$

b $B_{D32} = \dfrac{\text{Departure ground minutes saved}}{\text{Departure aircraft}_{32}} + \dfrac{\text{Departure air minutes}}{\text{Departure aircraft}_{32}}$

c $B_{C9} = \dfrac{\text{Crossing air minutes saved}}{\text{Crossing aircraft}_9}$

d $B_{C32} = \dfrac{\text{Crossing air minutes saved}}{\text{Crossing aircraft}_{32}}$

Step two: equate test results to the potential savings in a particular configuration

2a $B_{CROSS} = 1/27(14*B_{C9} + 13*B_{C32})$

b $B_{ARR} = B_{A9}$

c $B_{DEPT} = B_{D32}$

Step three: determine the make-up of a congested national sector.

3. Config(Sector X) = (% Arrival problem_X)
+ (% Departure problem_X)
+ (% Cross problem_X)

Step four: apply empirical aircraft delay savings according to the proportions in the congested national sector.

4a. Config. Savings(Sector X) = (% Arrival problem_X) * B_{ARR}
+ (% Departure problem_X) * ($B_{DEPT\text{-}AIR} + 0^n_{MIT} * B_{DEPT\text{-}GR}$)
+ (% Cross problem_X) * B_{CROSS}

Note 0^n_{MIT} is a 0/1 variable indicating positive ground delays when a flow restriction imposes delays on a major airport.

Scale the per aircraft delay by the number of aircraft in the congested national sector during the defined period of congestion

4b. Benefit_X = Config. Savings_X * aircraft_x
= % Arrival problem_X* aircraft_x * B_{ARR}
+ %Departure problem_X * aircraft_x * ($B_{DEPT\text{-}AIR} + 0^n_{MIT} * B_{DEPT\text{-}GR}$)
+ % Cross problem_X * aircraft_x * B_{CROSS}

Step five: find the annual burden of the problem

5. Annual Benefit_X = Benefit_X * Frequency that congested period occurs in a year_X

Step six: apply the economic values of minutes of delay

6. \$ of Annual Benefit = Days/year *

$$[\% \text{ Arrival problem}_X * \text{aircraft}_x * B_{ARR} * V_{AIR}$$
$$+ \%\text{Departure problem}_X * \text{aircraft}_x * (B_{DEPT\text{-}AIR} * V_{AIR} + 0^n{}_{MIT} * B_{DEPT\text{-}GR} * V_{GROUND})$$
$$+ \% \text{ Cross problem}_X * \text{aircraft}_x * B_{CROSS} * V_{AIR}]$$

NATIONAL BENEFIT RESULTS

En Route Center	Sector Name	Sector Altitude in FL		Path Configurations ARR	DEPT	OVR	Start Zulu	Stop *	A/C	Days per yr	Tot. Sect. Air Min.	Tot Sect. Grnd. Min.	Total Sector Losses	MIT ** Restrictions
1 Albuquerque	Gallop High	270	+	35%	15%	50%	18:15	20:00	63	308	167,442	0	$5,274,410	none
				35%	15%	50%	21:00	22:45	58	308				none
				35%	15%	50%	0:00	3:15	90	308				none
2 Atlanta	Sinca	SFC	230	75%	10%	15%	13:15	13:45	24	52	16,675	0	$525,257	none
				75%	10%	15%	15:45	17:15	45	52				none
				75%	10%	15%	22:15	23:00	21	52				none
3 Atlanta	Unarm	110	230	70%	15%	15%	13:30	16:15	90	260	141,176	0	$4,447,043	none
				70%	15%	15%	18:30	19:30	39	260				none
				70%	15%	15%	21:45	22:30	28	260				none
4 Atlanta	Leeon	110	230	70%	15%	15%	14:00	18:30	128	260	167,253	0	$5,268,471	none
				70%	15%	15%	20:15	21:15	30	260				none
				70%	15%	15%	23:15	0:15	28	260				none
5 Atlanta	Tiroe	SFC	230	***	***	***	***	***	40	246	140,522	0	$4,426,454	none
				80%	10%	10%	14:45	17:00	64	246				none
				80%	10%	10%	21:15	23:45	57	246				none
6 Atlanta	Spartanburg	240	290	25%	70%	5%	14:00	15:30	60	246	54,846	511,031	$15,116,640	20 MIT
				***	***	***	***	***	41 ***	246				20 MIT
7 Boston	Gardner	SFC	320	50%	10%	40%	12:00	13:45	62	285	173,868	0	$5,476,850	none
				50%	10%	40%	16:15	18:15	90	285				none
				50%	10%	40%	21:00	23:00	56	285				none
8 Boston	Danbury	110	270	20%	60%	20%	12:30	14:30	84	308	125,982	80,898	$6,087,957	10 MIT
				20%	60%	20%	23:30	1:30	87	308				10 MIT
9 Boston	Stewart	70	110	65%	15%	20%	11:15	12:15	39	308	128,301	133,287	$7,533,609	20 MIT
				65%	15%	20%	16:45	18:45	86	308				20 MIT
10 Boston	Athens	240	+	50%	40%	10%	16:45	18:30	82	308	178,245	537,413	$19,694,947	20 MIT
				50%	40%	10%	20:00	22:15	107	308				20 MIT
11 Chicago	Cribb	SFC	230	2%	90%	8%	12:00	13:45	108	308	338,756	659,733	$27,955,817	none
				2%	90%	8%	15:30	16:45	71	308				none
				2%	90%	8%	18:15	23:00	285	308				15 MIT
				2%	90%	8%	1:00	2:00	68	308				none

#	En Route Center	Sector Name	Sector Altitude in FL		Path Configurations ARR	DEPT	OVR	Start Zulu	Stop * Zulu	A/C	Days per yr	Tot. Sect. Air Min.	Tot Sect. Grnd. Min.	Total Sector Losses	MIT ** Restrictions
12	Chicago	Washington	240	350	2%	70%	28%	13:15	16:15	100	308	167,825	0	$5,286,474	none
					2%	70%	28%	17:30	19:15	75	308				none
					2%	70%	28%	22:15	0:45	100	308				none
13	Chicago	Peotone	100	230	1%	85%	14%	12:15	21:00	426	308	314,922	339,125	$18,805,126	10 MIT
					1%	85%	14%	22:15	0:15	80	308				10 MIT
14	Cleveland	Revenna	240	310	40%	20%	40%	11:15	12:30	57	278	119,649	202,753	$9,081,076	20 MIT
					40%	20%	40%	21:00	22:30	101	278				20 MIT
15	Cleveland	Lorraine	330	+	5%	5%	90%	11:30	15:15	167	260	265,736	0	$8,370,692	none
					5%	5%	90%	18:45	1:00	408	260				none
	Denver	none													
16	Fort Worth	Wichita Falls	240	+	80%	10%	10%	17:30	22:15	142	260	136,198	0	$4,290,233	none
17	Fort Worth	Quitman	110	230	5%	85%	10%	18:30	20:30	99	308	111,082	113,935	$6,484,181	10 MIT
					5%	85%	10%	22:30	23:45	71	308				10 MIT
18	Houston	Daisetta	SFC	230	90%	10%		13:30	16:15	85	260	149,600	0	$4,712,411	none
					90%	10%		19:00	21:00	61	260				none
19	Houston	Woodville	240	+	90%	10%		15:15	16:15	35	308	111,672	0	$3,517,674	none
					90%	10%		17:30	19:15	57	308				none
20	Indianapolis	King High	240	330	30%	20%	50%	13:00	15:00	70	230	127,357	237,816	$10,242,547	20 MIT
					30%	20%	50%	19:00	20:00	47	230				20 MIT
					30%	20%	50%	22:00	0:15	107	230				20 MIT
21	Indianapolis	Columbus Low	SFC	230	25%	50%	25%	13:00	0:00	476	308	362,855	917,766	$35,475,397	15 MIT
22	Jacksonville	Ocala Low	0	260	45%	45%	10%	13:45	14:30	30	206	74,937	0	$2,360,520	none
					45%	45%	10%	15:30	16:50	43	206				none
					45%	45%	10%	18:30	20:00	50	206				none
23	Jacksonville	Perry	240	310	40%	40%	20%	13:30	15:00	69	206	93,196	33,962	$3,825,492	10 MIT
					40%	40%	20%	17:15	19:30	92	206				10 MIT
24	Kansas City	Garden City High	240	+			100%	15:45	19:15	128	260	74,589	0	$2,349,547	none
							100%	21:30	22:45	48	260				none
25	Kansas City	Hallsville High	240	+	33%	34%	33%	13:15	15:45	94	260	273,923	91,427	$11,023,967	10 MIT
					33%	34%	33%	16:45	20:45	217	260				10 MIT
					33%	34%	33%	23:15	1:00	93	260				10 MIT

	En Route Center	Sector Name	Sector Altitude in FL		Path Configurations ARR	DEPT	OVR	Start Zulu	Stop * Zulu	A/C	Days per yr	Tot. Sect. Air Min.	Tot Sect. Grnd. Min.	Total Sector Losses	MIT ** Restrictions
26	Leesburg	Norfolk High	240	+	45%	45%	10%	14:45	17:15	78	30	14,906	40,370	$1,527,237	20 & 15 MIT
					45%	45%	10%	18:30	20:45	90	30				20 & 15 MIT
27	Leesburg	Marlington	?	?	80%	10%	10%	12:45	14:00	48	30	15,051	0	$474,110	none
					80%	10%	10%	17:30	20:00	88	30				none
28	Los Angeles	19	120	230	70%	30%		17:00	20:00	135	308	215,932	0	$6,801,849	none
					70%	30%		0:00	1:30	64	308				none
29	Los Angeles	35	240	+	25%	35%	40%	17:00	20:00	195	308	202,684	0	$6,384,561	none
					25%	35%	40%	0:00	2:30	78	308				none
30	Los Angeles	Eight	SFC	230	30%	55%	15%	17:00	20:00	92	308	119,544	0	$3,765,637	none
					30%	55%	15%	21:00	0:00	56	308				none
31	Los Angeles	Four	130	230	10%	80%	10%	15:00	16:00	65	308	167,288	153,911	$9,302,059	10 MIT
					10%	80%	10%	18:00	19:30	78	308				10 MIT
					10%	80%	10%	20:00	22:00	71	308				10 MIT
					10%	80%	10%	0:00	1:00	30	308				10 MIT
	Memphis	none													
32	Miami	Aluto	SFC	230		99%	1%	17:00	18:30	50	154	26,050	160,830	$5,034,328	20 & 10 MIT
						99%	1%	22:00	23:30	44	113				20 & 10 MIT
33	Miami	Hobee High	240	+	90%		10%	13:15	16:15	104	308	231,713	0	$7,298,950	none
					90%		10%	18:30	21:00	89	308				none
34	Miami	LAL High	100	230	50%	20%	30%	15:15	15:45	28	154	27,040	22,751	$1,447,843	15 MIT
					50%	20%	30%	17:30	18:15	31	154				15 MIT
35	Minneapolis	Mason City High	240	+	33%	34%	33%	16:15	20:30	147	308	196,785	0	$6,198,715	none
					33%	34%	33%	21:30	0:00	98	308				none
36	Minneapolis	Six	SFC	230	45%	50%	5%	12:15	13:30	82	308	268,837	115,512	$11,494,784	10 MIT
					45%	50%	5%	14:30	15:30	62	308				10 MIT
					45%	50%	5%	19:45	21:45	83	308				10 MIT
					45%	50%	5%	23:00	0:00	66	308				10 MIT
37	New York	Elmira High	230	+		65%	35%	12:00	14:30	78	260	83,903	0	$2,642,958	none
						65%	35%	22:00	1:00	91	260				none
38	New York	Milton High	240	+	80%	20%		12:00	18:45	128	308	345,986	0	$10,898,567	none
					80%	20%		19:30	23:00	173	308				none

	En Route Center	Sector Name	Sector Altitude in FL		Path Configurations ARR	DEPT	OVR	Start Zulu	Stop * Zulu	A/C	Days per yr	Tot. Sect. Air Min.	Tot Sect. Grnd. Min.	Total Sector Losses	MIT ** Restrictions
39	New York	Manta	70	230	20%	20%	60%	11:15	13:30	67	278	94,425	106,505	$5,764,837	15 MIT
					20%	20%	60%	15:15	18:30	86	278				15 MIT
40	Oakland	32	240	+		50%	50%	14:30	17:00	132	308	163,091	113,147	$8,101,803	10 MIT
						50%	50%	19:00	21:45	155	308				10 MIT
41	Oakland	33	240	+	50%	50%		14:30	22:00	378	308	523,118	0	$16,478,216	none
					50%	50%		2:30	3:45	81	308				none
					50%	50%		23:00	0:30	88	308				none
42	Salt Lake City	Tonopah High	310	+		1%	99%	15:00	18:30	125	260	97,731	0	$3,078,531	none
						1%	99%	20:00	21:45	105	260				none
43	Seattle	Six	SFC	230	20%	40%	40%	14:15	20:15	181	260	108,520	0	$3,418,391	none

TOTAL $337,746,173

* Intended Stop: APOLLO aircraft counts ended at 03:45 Z. Some west coast congestion periods reported lasting beyond 03:45 Z.

** MIT Restrictions that impact an identified large airport and cause ground delays. If an MIT is reported backing up an airport, ground delays are computed.

- The following per-minute test case savings were used for MIT restrictions: 20 MIT, 23.08 minutes; 15 MIT, 12.52 minutes; 10 MIT, 2.56 minutes.
- The Chicago ARTCC Cribb sector incurs ground delays only during 2/3 of the 18:15 to 23:00 problem period shown, The ground delay dollar losses are adjusted accordingly.
- Sectors showing two MIT restrictions apply these to two different airports during the same time period. Ground delay dollar losses are calculated by applying the loss associated with each MIT restriction to 50% of the total number of departures.

*** These sectors and time periods were tested in the simulation study. Dollar Benefits were calculated directly from the results presented in section 6.1 of the report, and included in the sector totals shown here.

EXPLANATION OF COLUMN HEADINGS:

Center - ARTCC containing sector.

ARR/DEPT/OVR - Column shows the percentage of traffic in that sector flying a problem configuration: arrivals, departures, overflight/crossing. Potential configuration savings were calculated to be Arrivals, 4.15 minutes; Departures 2.06 minutes (air only); Overflight1.63 minutes.

Zulu - Universal Coordinated Time, the time meter used in defining the daily congested period.

A/C - The number of aircraft in the sector during the congested period on a sample day.

Tot. Sect. Air Min. - The total minutes of air delays computed for a sector.

Tot. Sect. Grnd. Min. - The total minutes of ground delays computed for a sector.

U.S. GOVERNMENT PRINTING OFFICE: 1995 - 605-618